Solid Biofuels, Fuels and Their Characteristics

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Glossary

Woody fuels Biomass from trees, bushes, and shrubs.

Herbaceous fuels Biomass from plants that have a non-woody stem and which die back at the end of the growing season.

Pellets Densified biofuel made from pulverized biomass with or without additives usually with a cylindrical form, random length typically 5–40 mm, and broken ends. Max diameter: 25 mm.

Physical-mechanical properties Fuel characteristics such as surface properties, geometry, size and size distribution, fine matter content, flowing and bridging properties, resistance to abrasion, bulk, and particle density.

Biomass ash Solid mineral residue obtained from complete fuel combustion.

Energy density Ratio of net energy content and bulk volume.

Definition of the Subject

In the context of the future energy supply and renewable energies biomass is an energy source with a high potential and it has raised many expectations in society and politics. This high interest is also caused by the huge variety of possible resources and the many technical options of application for heating, electricity production, or mobility. The physical appearance of biofuels is also quite variable: biomass can be provided as solid, liquid, or gaseous fuel determining different technological conversion paths.

However, the overview presented here is limited to solid biomass resources. The paper aims at understanding the specialties of natural solid biomass fuels, which are directly used for thermochemical conversion mainly by an end user who has the goal to produce heat and/or electricity. Therefore, raw materials for biological conversion (e.g., fermentation for biogas production) are not characterized. This is also true for those resources that are relevant for non-thermochemical upgrading processes as applied for the production of liquid biofuels (e.g., physical extraction or ethanol fermentation).

Any biomass-containing waste streams are also not considered here, even if they are used for energetic purposes. The goal is rather to define, present and discuss the properties of the main natural untreated solid biomass fuels, which are either residues or field crops, and to indicate the consequences for the conversion process.

Introduction

The provision of solid biofuels that meet high quality standards is becoming increasingly important in order to fulfill the rising technical and environmental requirements for their utilization. The process of a thermochemical conversion is largely influenced by the fuel properties, and this applies to the pollutant formation. Therefore, the specific characteristics of the respective fuels have to be adequately regarded. It is also essential to understand their impact in the conversion process in order to assess their importance and to evaluate chances for improvements. This is a major goal of the here presented study.

The avoidance of unfavorable fuel properties can only be considered if the reasons for any excessive fuel related phenomenons are known and can be explained. It is therefore important to analyze the production chain and to identify the key impacts for fuel quality.

In general, quality-determining factors of biomass fuels can be attributed to two major phases of the life cycle: the growing phase, in which mainly the compositional characteristics are developed, and the supply

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phase, in which mostly the physical-mechanical parameters determined (Fig. 1). Only some of the quality influencing factors identified during these phases have been studied and can be quantified at least to some extend with regard to their effectiveness [27].

In view of the influences and the history of the fuel provision as outlined in Fig. 1, the selection and specification of the suitable fuel for a given process is thus an essential part of the optimization strategy of an energy use concept for biomass. Both, the direct determination of the critical quality parameters as well as the fuel assessment by knowing the species and the influences along the provision chain can lead to a sound assessment of the fuels applicability.

Fuel Characterization Schemes and Overview

Fuel specification can either be done directly, by determining the relevant fuel parameters, or indirectly, by retracing the fuel to the origin and/or to the actual species which allows fuel assessment through experience. Both approaches are discussed in the following.

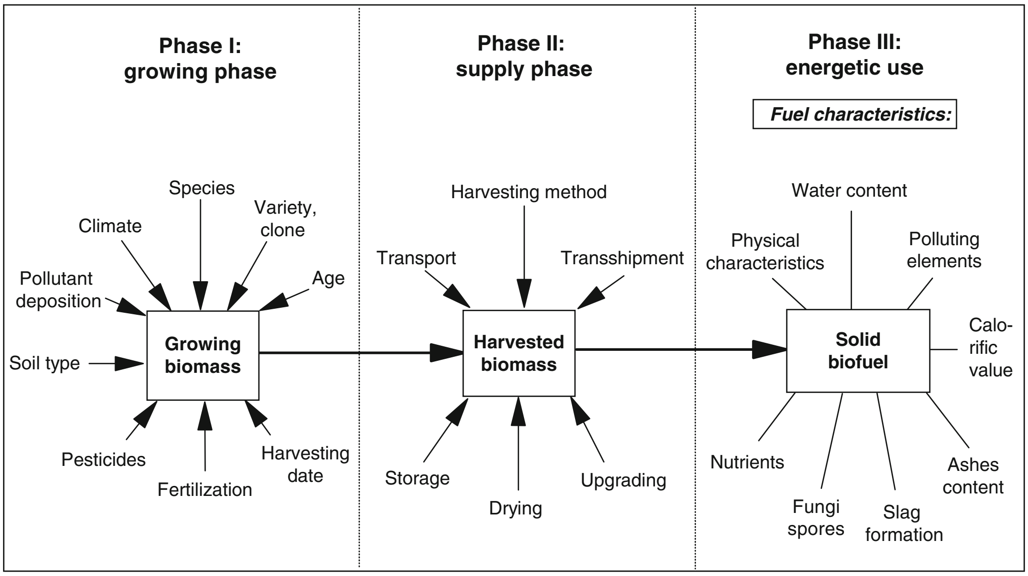
Characterization by Determining Specific Fuel Properties

For the energetic use, three groups of characteristics are decisive: the elementary composition, the technical combustion properties, and the physical-mechanical properties (Table 1). Sometimes the last two groups are also compiled as "physical parameters." Most of the parameters allocated to the three groups are quality-relevant parameters, because they can influence the thermochemical and the pollutant formation processes or they are determining the usability of the produced ash or slag residues.

Below therefore the significance of each of the presented fuel parameter is discussed individually. This applies to the characteristics as listed in Table 1, which can serve as an overview of important fuel properties. For better understanding of the thermochemical conversion processes (i.e., pyrolytic decomposition, gasification and oxidation) the main macromolecular constituents of lignocellulose biomass fuels are also presented in the following.

Characterization by Origin

Many of the measurable fuel parameters and their usual variation are already determined by the fuel origin, which is described either by the species or raw material type or by the processes for harvesting and treatment. The description and the retracing of fuels to their origin is therefore an essential element of an effective quality assurance management for solid biofuels. Therefore,



Solid Biofuels, Fuels and Their Characteristics. Figure 1
Factors influencing the quality of solid biofuels ([27], modified)

Solid Biofuels, Fuels and Their Characteristics. Table 1 Quality relevant characteristics of biomass fuels and their impact in the utilization chain

Quality parameter	Main impact
Element concentration	
Carbon (C)	Calorific value, oxygen demand, particle emissions
Hydrogen (H)	Calorific value, oxygen demand
Oxygen (O)	Calorific value, oxygen demand
Nitrogen (N)	NO_x- and N_2O-emission
Potassium (K)	Ash softening behavior, high temperature corrosion, particle emission
Magnesium (Mg)	Ash softening behavior, ash embedding of pollutants, ash utilization, particle emission
Calcium (Ca)	Ash softening behavior, ash embedding of pollutants, ash utilization, particle emission
Sulfur (S)	SO_x-emissions, high temperature corrosion, particle emission
Chlorine (Cl)	Emissions of HCl and halogen-organic compounds (e.g., PCDD/F), high temperature chlorine corrosion, particle emission
Heavy metals	Ash utilization, heavy metal emissions, catalytic impacts (e.g., in PCDD/F-formation), particle emission
Technical combustion properties	
Moisture content	Calorific value, storability (losses by biodegradation, self ignition), fuel weight, combustion temperature
Calorific value	Energy content of fuel, dimensioning of combustion plant
Ash content	Particle emission, residue management and utilization
Ash melting behavior	Slag formation and deposits, operational safety and -continuity, maintenance requirements
Physical-mechanical properties	
Shape and dimensions	Allocation to mechanical systems and furnace types, bridging properties, ignitability, drying speed
Size classification/Fine matter content	Clogging in conveyors, flowability and bridging properties, aeration and drying properties, dust formation, risk of explosion
Bridging properties	Flowability, failures during transhipment and storage extraction
Bulk density	Storage and transport efforts, power requirement of conveyor motors, volume of storage
Particle density	Bulk density, pneumatic conveying properties, combustion properties (specific heat conductivity, etc.)
Resistance to abrasion	Amount of fines (dust formation, demixing)

a uniform identification system was elaborated in the course of the European standardization process for solid biofuels [18]. In this system, the possible features of origin and/or the biomass fractions are comprehensively defined following a hierarchical classification and enumeration scheme. It allows characterizing the given fuel with variable levels of detail, depending on the knowledge about the fuel. This is done by distinguishing four major groups [18]:

- Woody biomass (digit 1)
- Herbaceous biomass (digit 2)
- Fruit biomass (digit 3)
- Blends and mixtures (digit 4)

Theses major groups are divided into several other groups and subgroups. As an example, Figs. 2 and 3 show the classification for the two largest groups, the woody and herbaceous fuels. The given labeling numbers allow a simple reference to specific fuels or fuel groups (e.g., to be used in directives, contracts, or fuel quality standards).

Also the third major group (fruit biomass) is divided into several subclasses. Here a differentiation between orchard and horticulture fruits, by-products and residues from fruit processing industry, as well as blends and mixtures is made. Both subgroups have further subdivisions [18].

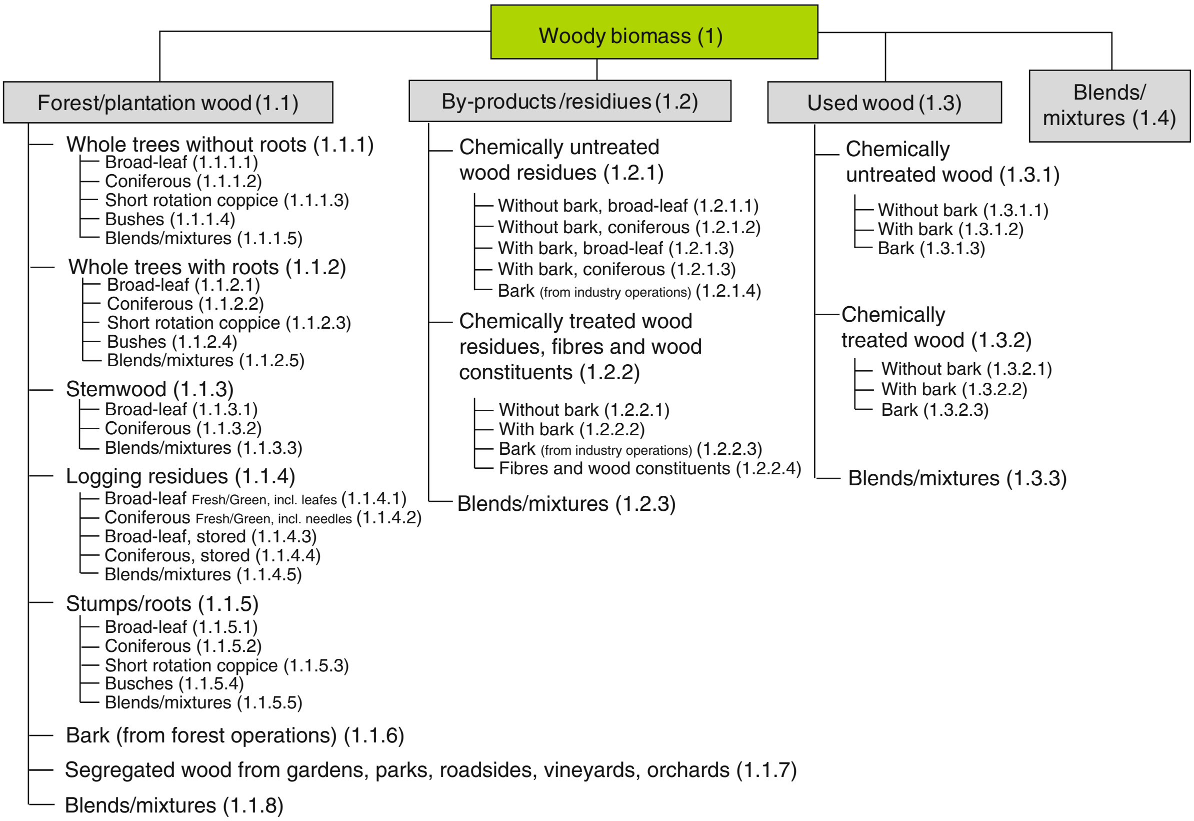
The term "blends and mixtures" not only used for the fourth major group but also for several sub-groups is addressing raw materials of variable origin within the given group in the classification scheme and it appears on all four levels. Blends are defined as intentionally mixed biomass, whereas mixtures are unintentionally mixed biomass. A mixture between chemically treated and untreated material is to be classified as a chemically treated fuel [18].

Fuel Composition

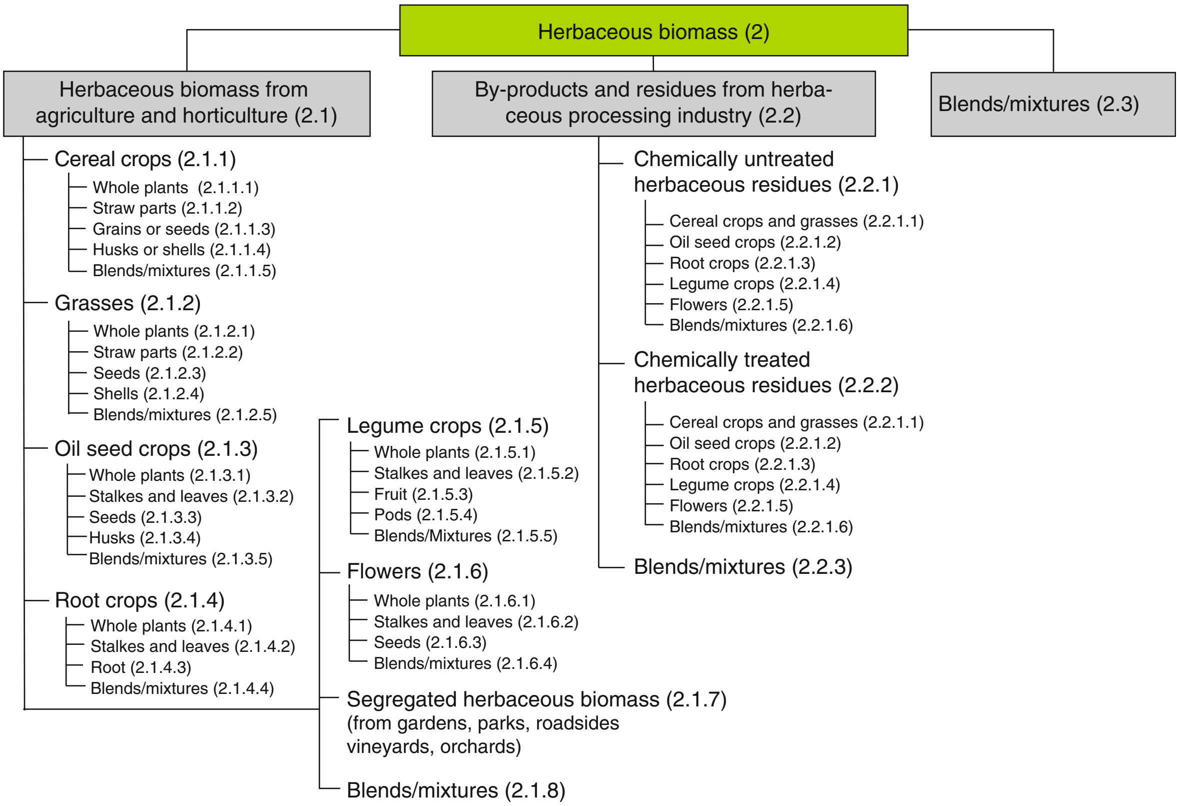
Molecular Composition

Biomass fuels are consisting of the three biopolymers cellulose, hemicellulose, and lignin. They usually provide more than 95% of the plants dry matter. As further groups of components, the extractives (e.g., fat and resin) and the ash need to be mentioned. Annually harvested crops can also contain a significant amount of protein. The share of masses for these main constituents in wood and herbaceous fuels is given in Table 2.

Among all organic substances, the cellulose is most widespread in nature. Cellulose forms the structural


Woody biomass (1)
Forest/plantation wood (1.1)
Whole trees without roots (1.1.1)
Broad-leaf (1.1.1.1)
Coniferous (1.1.1.2)
Short rotation coppice (1.1.1.3)
Bushes (1.1.1.4)
Blends/mixtures (1.1.1.5)
Whole trees with roots (1.1.2)
Broad-leaf (1.1.2.1)
Coniferous (1.1.2.2)
Short rotation coppice (1.1.2.3)
Bushes (1.1.2.4)
Blends/mixtures (1.1.2.5)
Stemwood (1.1.3)
Broad-leaf (1.1.3.1)
Coniferous (1.1.3.2)
Blends/mixtures (1.1.3.3)
Logging residues (1.1.4)
Broad-leaf Fresh/Green, incl. leafes (1.1.4.1)
Coniferous Fresh/Green, incl. needles (1.1.4.2)
Broad-leaf, stored (1.1.4.3)
Coniferous, stored (1.1.4.4)
Blends/mixtures (1.1.4.5)
Stumps/roots (1.1.5)
Broad-leaf (1.1.5.1)
Coniferous (1.1.5.2)
Short rotation coppice (1.1.5.3)
Busches (1.1.5.4)
Blends/mixtures (1.1.5.5)
Bark (from forest operations) (1.1.6)
Segregated wood from gardens, parks, roadsides, vineyards, orchards (1.1.7)
Blends/mixtures (1.1.8)
By-products/residiues (1.2)
Chemically untreated wood residues (1.2.1)
Without bark, broad-leaf (1.2.1.1)
Without bark, coniferous (1.2.1.2)
With bark, broad-leaf (1.2.1.3)
With bark, coniferous (1.2.1.3)
Bark (from industry operations) (1.2.1.4)
Chemically treated wood residues, fibres and wood constituents (1.2.2)
Without bark (1.2.2.1)
With bark (1.2.2.2)
Bark (from industry operations) (1.2.2.3)
Fibres and wood constituents (1.2.2.4)
Blends/mixtures (1.2.3)
Used wood (1.3)
Chemically untreated wood (1.3.1)
Without bark (1.3.1.1)
With bark (1.3.1.2)
Bark (1.3.1.3)
Chemically treated wood (1.3.2)
Without bark (1.3.2.1)
With bark (1.3.2.2)
Bark (1.3.2.3)
Blends/mixtures (1.3.3)
Blends/mixtures (1.4)

Solid Biofuels, Fuels and Their Characteristics. Figure 2
Classification and enumeration scheme for woody biomass by origin and biomass fractions (according to EN 14 961-1 [18])


Herbaceous biomass (2)
Herbaceous biomass from agriculture and horticulture (2.1)
By-products and residues from herbaceous processing industry (2.2)
Blends/mixtures (2.3)
Cereal crops (2.1.1)
Whole plants (2.1.1.1)
Straw parts (2.1.1.2)
Grains or seeds (2.1.1.3)
Husks or shells (2.1.1.4)
Blends/mixtures (2.1.1.5)
Grasses (2.1.2)
Whole plants (2.1.2.1)
Straw parts (2.1.2.2)
Seeds (2.1.2.3)
Shells (2.1.2.4)
Blends/mixtures (2.1.2.5)
Oil seed crops (2.1.3)
Whole plants (2.1.3.1)
Stalkes and leaves (2.1.3.2)
Seeds (2.1.3.3)
Husks (2.1.3.4)
Blends/mixtures (2.1.3.5)
Root crops (2.1.4)
Whole plants (2.1.4.1)
Stalkes and leaves (2.1.4.2)
Root (2.1.4.3)
Blends/mixtures (2.1.4.4)
Legume crops (2.1.5)
Whole plants (2.1.5.1)
Stalkes and leaves (2.1.5.2)
Fruit (2.1.5.3)
Pods (2.1.5.4)
Blends/Mixtures (2.1.5.5)
Flowers (2.1.6)
Whole plants (2.1.6.1)
Stalkes and leaves (2.1.6.2)
Seeds (2.1.6.3)
Blends/mixtures (2.1.6.4)
Segregated herbaceous biomass (2.1.7)
(from gardens, parks, roadsides
vineyards, orchards)
Blends/mixtures (2.1.8)
Chemically untreated herbaceous residues (2.2.1)
Cereal crops and grasses (2.2.1.1)
Oil seed crops (2.2.1.2)
Root crops (2.2.1.3)
Legume crops (2.2.1.4)
Flowers (2.2.1.5)
Blends/mixtures (2.2.1.6)
Chemically treated herbaceous residues (2.2.2)
Cereal crops and grasses (2.2.1.1)
Oil seed crops (2.2.1.2)
Root crops (2.2.1.3)
Legume crops (2.2.1.4)
Flowers (2.2.1.5)
Blends/mixtures (2.2.1.6)
Blends/mixtures (2.2.3)

Solid Biofuels, Fuels and Their Characteristics. Figure 3
Classification and enumeration scheme for herbaceous biomass by origin and biomass fractions (according to EN 14 961-1 [18])

substance of the cell wall and it is responsible for the tensile strength of biomass. Cellulose consists almost fully of congenerous D-glycoside molecules which are linked via a ß-(1–4)-binding to form an unbranched polysaccharide (Fig. 4). The degree of polymerization or the length of the chain can vary widely. Depending on the wood species it can reach up to 14,000 molecules [47].

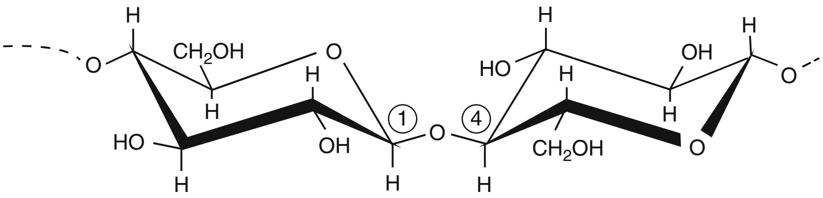
The term hemicellulose (also polyose) specifies a second important group of biopolymers. Hemicellulose is a branched polysaccharide formed by various monomeric units. Their function in the plant is manifold. They serve as structural element in the cell membrane, as reserve material, or they act cell wall cementating through their adhesive properties. Hemicellulose in detail is either hexose (glucose, mannose and galactose), pentose (arabinose, xylose), desoxyhexose, or one of various hexuronic acids.

The actual filling material of lignocellulose materials is lignin. It does not appear as independent material but it is always a companion of the cellulose. Due to its cementation properties it is responsible for the pressure resistance of wood. Lignin is a three dimensionally linked aromatic polymer compound with alcyl-benzol-structure. It consists of variously bound phenylpropane units substituted by hydroxyl and methoxyl groups (Fig. 5). A strong lignification ensures that the sprout of the plant can remain in the upright position when the water pressure (turgor) usually responsible for stability of less lignified plants becomes weak. Therefore, strongly lignified materials (e.g., wood) have relatively low moisture content. Wood fuels have a lignin content of 20–30%, while for annually harvested plants it is usually below 20% (Table 2).

In lignin the carbon content is significantly higher (64%) than for cellulose (42%). Differences in the

Solid Biofuels, Fuels and Their Characteristics. Table 2 Share of cellulose, hemicellulose, lignin, and other components in various biomass fuels ([24, 41, 40]; no specification is made concerning the deviation to 100% mass; *na* not available)

Fuel	Cellulose	Hemicellulose	Lignin	Resin/fat	Protein	Ash
Wood fuel species (data given in % of dry matter)						
Fir	42.3	22.5	28.6	2.3	–	1.2
Pine	41.9	21.5	29.5	3.2	–	1.3
Spruce	41.0	24.3	30.0	n.a.		na
Ash	40.2	25.0	26.0	2.2	–	1.3
Beech	45.4	22.2	22.7	0.7	–	1.6
Birch	40.9	27.1	27.3	2.2	–	1.8
Poplar	48.4	18.2	21.6	2.4	–	1.3
Willow	42.9	21.9	24.7	2.0	–	1.2
Herbaceous fuels (data given in % of dry matter)						
Wheat straw	38	29	15	–	4	6
Prairie grass	37	29	19	–	3	6
Miscanthus	43	24	19	–	3	2
Sweet sorghum	23	14	11	–	n.a.	5
Tall fescue	25	25	14	–	13	11
Maize straw	38	26	19	–	5	6



Solid Biofuels, Fuels and Their Characteristics. Figure 4
Chemical structure of cellulose

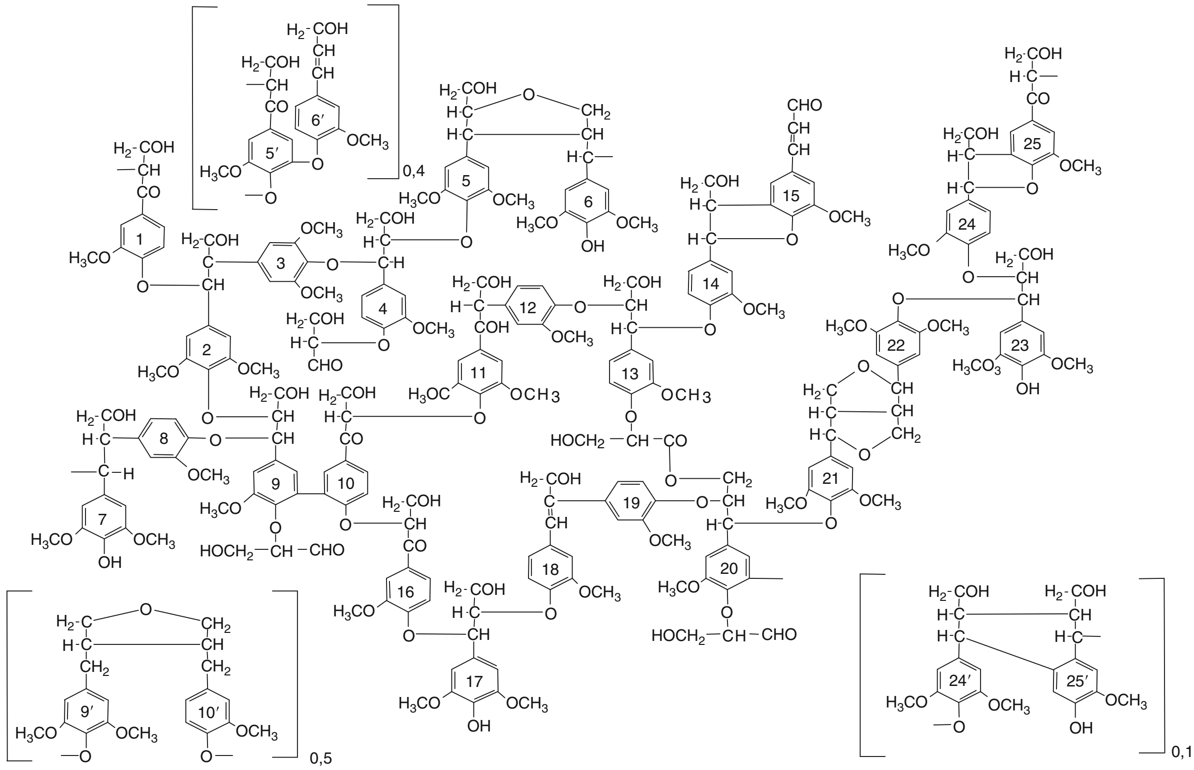
macromolecular composition are therefore directly influencing the total carbon content as the main determinant for the calorific value of the dry matter. High contents of lignin and extractives are therefore raising the calorific value (section "Calorific Value").

Elemental Composition

Plant biomass is composed of many elements, of which 26 are known to be essential for growth. They can be distinguished between main elements and trace elements.

The main elements are carbon (C), oxygen (O), and hydrogen (H), which arise from the CO_2-assimilation and the H_2O-uptake, and the six major nutrients nitrogen (N), potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg), and sulfur (S), as well as the also relatively prevalent chlorine (Cl), which does not count as a nutrient. These elements are either decisively contributing to biomass formation or they play an important role as associated material in plant nutrition.

Apart from these elements the plant mass also contains trace elements such as silicon (Si), sodium (Na),



Solid Biofuels, Fuels and Their Characteristics. Figure 5
Chemical structure of beech wood lignin [45]

iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), cobalt (Co), lead (Pb), aluminum (Al), chrome (Cr), cadmium (Cd), nickel (Ni), mercury (Hg) or arsenic (As). Several of them are listed as essential micro nutrients while others can be harmful to plant life. The usual concentrations of these elements and their impact on in thermochemical conversion are discussed below.

Main Elements *Carbon, oxygen, hydrogen.* Solid biomass consists mainly of carbon (C), oxygen (O), and hydrogen (H). The component that most determines the release of heat via oxidation is the carbon. Hydrogen also provides energy by oxidations while oxygen supports these reactions. Woody fuels contain the highest carbon content among the biomass materials (about 47–50 mass-% in dry matter). Non-woody biomass fuels have a carbon content of 43–48%. Their oxygen content is between 40% and 45% (dry basis) and for hydrogen the content is between 5% and 7% (see Table 3).

From these data the molecular formula for wood is around $CH_{1.44}O_{0.66}$. Significantly, higher carbon contents are given for biomass with high oil content (e.g., rapeseeds). A higher share of non-burning constituents (ash) can cause lower carbon content. This, for example, applies to roadside woodcuttings with usually have a higher ash content.

Opposite to coal (e.g., hard coal, brown coal), which are an outcome of a natural carbonization process, the carbon in solid biofuels is prevailing in a partly oxidized mode with a respectively higher oxygen content, thus having a lower carbon concentration. This explains the lower caloric value compared to fossil coal (Table 6).

Nitrogen. The nitrogen(N)-content varies significantly between different biomass types. This variation reflects the differences in composition of solid biomass. High protein containing plants or plant fractions are always higher in nitrogen content than typical lignocellulose materials as wood or straw. This applies mainly to the generative parts of crops like grain, oil

Solid Biofuels, Fuels and Their Characteristics. Table 3 Contents of main elements in untreated natural biomass fuels compared to hard and brown coal (mean values according to [31], for coal: [56])

	C	H	O	N	K	Ca	Mg	P	S	Cl
Biomass fuel	**in % of dry matter**									
Hard coal	72.5	5.6	11.1	1.3					0.94	<0.13
Brown coal	65.9	4.9	23.0	0.7					0.39	<0.1
Spruce wood (with bark)	49.8	6.3	43.2	0.13	0.13	0.70	0.08	0.03	0.015	0.005
Beech wood (with bark)	47.9	6.2	45.2	0.22	0.15	0.29	0.04	0.04	0.015	0.006
Poplar (short rotation)	47.5	6.2	44.1	0.42	0.35	0.51	0.05	0.10	0.031	0.004
Willow (short rotation)	47.1	6.1	44.3	0.54	0.26	0.68	0.05	0.09	0.045	0.004
Bark (coniferous)	51.4	5.7	38.7	0.48	0.24	1.27	0.14	0.05	0.085	0.019
Rye straw	46.6	6.0	42.1	0.55	1.68	0.36	0.06	0.15	0.085	0.40
Wheat straw	45.6	5.8	42.4	0.48	1.01	0.31	0.10	0.10	0.082	0.19
Triticale straw	43.9	5.9	43.8	0.42	1.05	0.31	0.05	0.08	0.056	0.27
Barley straw	47.5	5.8	41.4	0.46	1.38	0.49	0.07	0.21	0.089	0.40
Rapeseed straw	47.1	5.9	40.0	0.84	0.79	1.70	0.22	0.13	0.27	0.47
Maize straw	45.7	5.3	41.7	0.65					0.12	0.35
Sunflower straw	42.5	5.1	39.1	1.11	5.00	1.90	0.21	0.20	0.15	0.81
Hemp straw	46.1	5.9	42.5	0.74	1.54	1.34	0.20	0.25	0.10	0.20
Rye whole plants	48.0	5.8	40.9	1.14	1.11		0.07	0.28	0.11	0.34
Wheat whole plants	45.2	6.4	42.9	1.41	0.71	0.21	0.12	0.24	0.12	0.09
Triticale whole plants	44.0	6.0	44.6	1.08	0.90	0.19	0.09	0.22	0.18	0.14
Rye kernels	45.7	6.4	44.0	1.91	0.66		0.17	0.49	0.11	0.16
Wheat kernels	43.6	6.5	44.9	2.28	0.46	0.05	0.13	0.39	0.12	0.04
Triticale kernels	43.5	6.4	46.4	1.68	0.62	0.06	0.10	0.35	0.11	0.07
Rapeseed kernels	60.5	7.2	23.8	3.94					0.10	
Miscanthus	47.5	6.2	41.7	0.73	0.72	0.16	0.06	0.07	0.15	0.22
Hay (nature conservation)	45.5	6.1	41.5	1.14	1.49	0.50	0.16	0.19	0.16	0.31
Tall fescue	41.4	6.3	43.0	0.87	1.94	0.38	0.17	0.17	0.14	0.50
Ryegras	46.1	5.6	38.1	1.34					0.14	1.39
Gras from roadsides	37.1	5.1	33.2	1.49	1.30	2.38	0.63	0.19	0.19	0.88

seeds, and protein plants, but it is also true for herbaceous crops, which have a high value as animal feed. Correspondingly, the nitrogen content is relatively high for grain kernels, whole grain plants and animal feed grass. Spruce wood contains only little nitrogen of around 0.1–0.2% (1,000–2,000 mg/kg) in the dry matter, while grain straw ranges in the order of 0.5% (Table 3). Also slightly increased nitrogen contents are observed for short rotation coppice; this is explained by the higher content of bark in the total wood mass.

The variations within a specific biomass assortment are usually relatively low for wood. This is demonstrated by the frequency distribution of certain concentration classes (Fig. 7). Concentrations of above 0.6% or below 0.3% are, for example, quite rare in wood fuels. Higher values and variation are given for straw from rapeseed, maize, sunflower, or hemp crops. The higher variation of nitrogen concentrations in herbaceous fuels is mainly due to differences in fertilization (e.g., different fertilization level or fertilization timing).

The nitrogen content of the fuel is directly affecting the formation of nitrogen oxides (NO_x) because this element is usually completely released into the volatile phase during combustion or gasification. The oxidation of the chemically bound nitrogen in the fuel is by far the most relevant formation path for NO_x. Therefore, the NO_x formation is usually declining with lower N-content in the fuel. Nitrogen embedding into the ash hardly happens. Nitrogen can also be responsible for the formation of N_2O (laughing gas) which is harmful to the climate.

Potassium. Similar to nitrogen there are also major differences in the potassium (K)-content between periodically fertilized field crops and perennial wood cultures usually not fertilized (e.g., forest or short rotation coppice). However, the potassium is – other than for nitrogen – not mostly prevalent in the generative parts of the plants, but it occurs mainly in the sprout and leaves. Therefore the potassium content of grain kernels is low (ca. 0.5–0.7% or 5,000–7,000 mg/kg, dry basis) while grain straw usually has K-concentrations around or above 1% (Table 3). Wood fuels however show potassium contents of hardly higher than 0.35% and their variation is low. This is not the case for grain straw, where the concentration varies between 0.2% and 2.5%. This larger bandwidth is not only a result of variable fertilization levels. It can be caused by differences in leaching by precipitation during the phase between ripening and harvest [31, 53].

Potassium is involved in the corrosion process on heat exchangers or on flue gas conducting parts of a furnace. The participation of potassium (and sodium) in corrosion is based on the fact that these elements can form gaseous alkali chlorides which condense and deposit on heat exchanger surfaces or on fine particles during cooling. These deposits can react with sulfur dioxide (SO_2) from the flue gas on heat exchanger surfaces and form alkali sulfates and elementary chlorine (Cl_2). The latter can diffuse though the porous cinder layers toward the tube surface of the heat exchanger where it is reduced to iron chloride ($FeCl_2$) due to the prevailing reductive conditions. Under the large temperature differences within the layer of deposits on the heat exchanger the partial pressure of $FeCl_2$ is differing largely. This allows the $FeCl_2$ gaseous under the prevailing conditions to diffuse away from the tube surface where they again undergo oxidizing conditions. The iron is thus oxidized again and a part of the released chlorine is repeatedly available for the corrosion process (so-called high temperature chlorine corrosion, Fig. 6) [48].

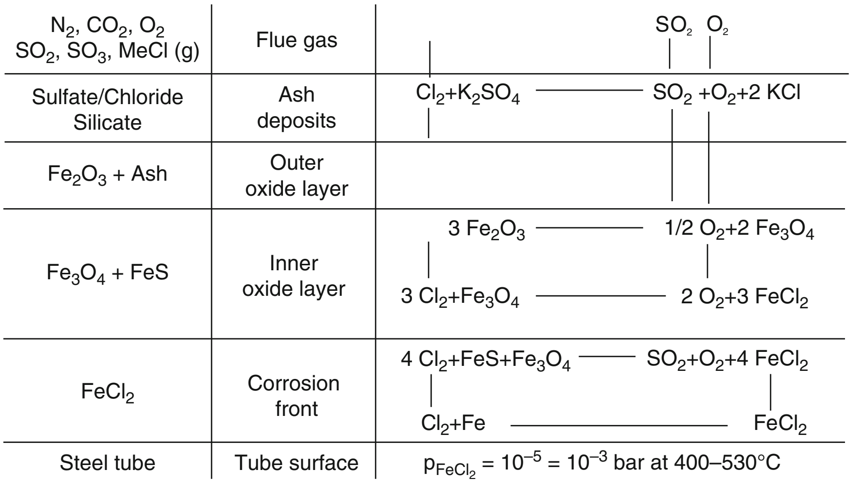
In the oxide state, potassium becomes volatile during combustion and only after cooling in the course of the flue gas tract it is condensed as fine particle. Therefore, potassium is listed among the aerosol forming elements of biofuel components [3]; this property can cause significant increases of particle emissions [35].

Potassium also influences the ash softening properties of a biofuel as it lowers the melting temperature of the ash (section "Ash Melting Properties"). The largest share of the potassium is thus embedded into the solid ash residues.

Calcium, magnesium, phosphorus. Biomass contains calcium (Ca), magnesium (Mg), and phosphorus (P). The calcium content ranges between 0.3% and 1% (for bark even higher), but in herbaceous fuels it can be significantly higher. The calcium content is low in grain straw and kernels. But it can be high in straw from other crops (e.g., rapeseed straw, sunflower straw) (Table 3).

In the combustion process, calcium improves the ash softening behavior by increasing the melting temperature of the ash (section "Ash Melting Properties"). For several fuels with an unfavorable ash-melting behavior, it can therefore be useful to mix calcium-containing additives (e.g., lime) to the fuel in order to raise the ash melting point [57]. High contents of alkaline earth elements (mainly Ca) can also lead to a higher embedding of sulfur into the ash, thus preventing the sulfur to be released as harmful SO_2 via the flue gas.

The manganese(Mg)-content in wood fuels is relatively low (ca. 0.04–0.1%). This is also true for phosphorus which is usually found in concentrations of <0.1% (for wood) or about 0.2% (herbaceous fuels) (Table 3). The three elements calcium, magnesium, and phosphorus increase the fertilization value of the ash.



Solid Biofuels, Fuels and Their Characteristics. Figure 6
Mechanism of high temperature chlorine corrosion at a heat exchanger surface [48]

Sulfur. The sulfur(S)-content in biomass fuels is strongly depending on the given macromolecular composition. For some amino acids and enzymes sulfur is required as an essential crop nutrient, but mostly only low quantities have to be provided by fertilization. However, the sulfur supply is usually significantly higher for field crops than for unfertilised woodland or for hardly fertilized short rotation coppice. Rapeseed straw has an average sulfur content of 0.3% in the dry matter. This is the highest among the biomass fuels. For wood fuels a sulfur content in the range of 0.02–0.05% can be expected and for grain straw the S-content is usually below 0.1% (Table 3). In general biomass fuels are low sulfur containing fuels.

In a complete thermochemical conversion, the sulfur oxide emissions are mainly determined by the sulfur content in the applied fuel. Sulfur is mostly changing into the gaseous phase by forming SO_2, SO_3, and alkali sulfates [48]. Similar to chloride, sulfur compounds can also condense during the cooling phase of the flue gas while forming alkaline or alkaline earth sulfates which are deposited either on heat exchanger surfaces or on other flue gas particles. A large portion of the sulfur content in the fuel (ca. 40–90%) is embedded into the ash, depending on the degree of particle separation by the applied flue gas purification system.

Sulfur can also indirectly contribute to increased corrosion (e.g., on heat exchanger surfaces). This can occur at higher SO_2-concentrations in the flue gas. Due to an increased sulfate binding in the prevailing alkaline and alkaline earth chloride compounds a release of corrosive chlorine (Cl_2) is supported [48].

Under certain circumstances, sulfur can also play a role in preventing the formation of dioxin and furan (PCDD/F). This can happen by changing and inactivating the catalytically acting copper oxides. In coal combustion, for example, a PCDD/F inhibiting effect is observed when the Cl/S-ratio in the fuel falls below 1.0. The chlorination or aromatics during PCDD/F-formation is usually even fully prevented at a Cl/S-ratio below 0.1 [25, 56].

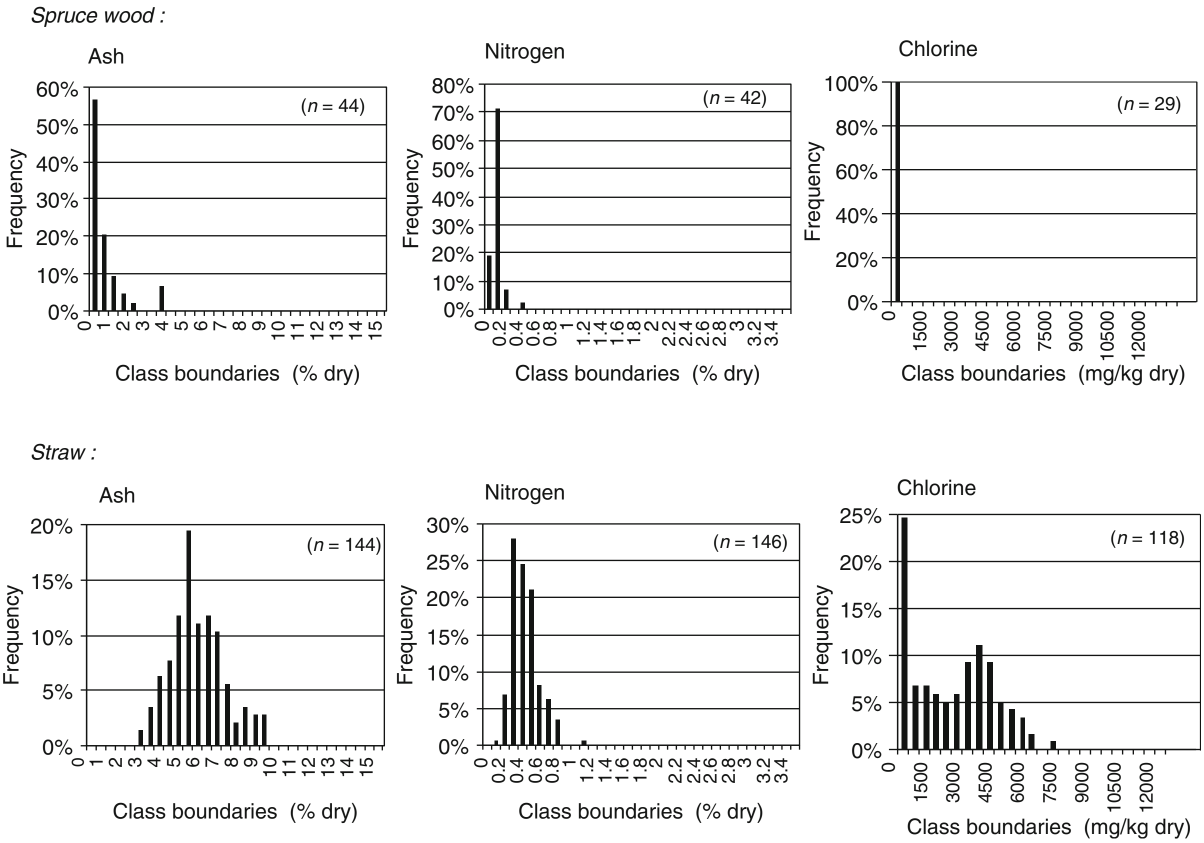
Chlorine. Chlorine (Cl) is a major associated material in potassium fertilizers [31]. Therefore its content in herbaceous biomass fuels is significantly higher than in wood fuels. This is because in forest operations and in short rotation forestry practice fertilization does usually not happen.

Consequently wood fuels show very low chlorine contents of about 0.005–0.02% in the dry matter. Often these contents are even below the detection limits of the applied methods. But for grain straw the chlorine content is several times higher (ca. 0.2–0.5%) and in coastal areas even concentrations of more than 1% are possible. Very high Cl-content is often observed in straw from rapeseed and sunflower (ca. 0.5–0.8%). This is also true for conventional hay (e.g., from ryegrass) (Table 3).

For the chlorine content, the bandwidth of variation is relatively high. In non-wood crops [31] this variation is on the one hand caused by the variable chlorine freight transported onto the land by fertilization and on the other hand it is influenced by leaching from the soil or from the died-off crop through precipitation. Such leaching from the crop can account for 60–80% chlorine reduction in the fuel [31, 53]. Therefore the leached "gray" straw is – from the viewpoint of combustion – always preferable compared to any fresh "yellow" straw. Both straw qualities are usually available in a region or during a harvesting season, thus the frequency distribution curve for the chlorine concentrations follows a pattern with a peak on the left side (Fig. 7).

The significance of chlorine in a thermochemical conversion process is manifold. For example, Chlorine is participating in the formation of hydrogen chloride (HCl) and dioxin/furan (PCDD/F) [38, 39, 48]. In spite of a high chlorine embedding into the ash between 40% and 95% [48], the HCl emissions via flue gas can be critical for certain Cl-rich fuels (e.g., grain straw) which then require secondary flue gas treatment. Furthermore, chlorine is acting corrosive at the surface of heat exchangers. This happens in interaction with alkaline and alkaline earth metals and with sulfur dioxide (SO_2). Additionally, chlorine is known to be an aerosol forming element [3], which can contribute to increasing particulate matter emissions during combustion [35].

Trace Elements All remaining elements are defined as trace elements. They are mostly heavy metals. These elements mainly determine the quality and usability of



Solid Biofuels, Fuels and Their Characteristics. Figure 7
Frequency distribution of values for selected fuel parameters measured in spruce wood and grain straw (*n* number of data) [31]

the ash accumulated during combustion or gasification. The easy volatile heavy metals cadmium (Cd), lead (Pb), and zinc (Zn) are listed as major aerosol forming elements increasing the emissions of particulate matter during combustion [3].

Opposite to the main elements, the variation of the trace element content is largely higher and less predictable. But some general trends and differences between the untreated natural fuels can be identified. Wood fuels from the forests, for example, are usually higher in heavy metal content than annually harvested crops. Particularly the bark from spruce wood takes here a top position for most heavy metals (for As, Cd, Co, Fe, Hg, Mn, Mo, Ni, and Zn). For the other wood fuels a differentiation has to be made between the long-term growing forest trees and the short rotation coppice (e.g., poplar, willow), where forest wood has almost consistently higher heavy metal contents. This is primarily due to the long rotation time where the forest trees are exposed to heavy metal depositions from the atmosphere. A second explanation is given by the fact that the pH-value of forest soils are usually low, which leads to a higher heavy metal solubility and thus to an increased element uptake via the roots.

An exception is here given for cadmium, which is relatively high in young willow trees due to a specific capturing ability which is given for this crop. Therefore, willow can be used for melioration of cadmium polluted fields [31, 54]. Apart from cadmium, the content of nickel, chrome, and mainly mercury, lead, and molybdenum is usually quite low for short rotation coppice.

The heavy metal content represents an important characteristic for the differentiation between naturally untreated and treated or used fuels. Increased heavy metal contents are often observed for grass cuttings or wood from roadsides [31]. Therefore some heavy metals are used as lead indicators for any nonnatural or untreated background. For example, a rapid test was developed for zinc (combined with the element chlorine) which is determined in the accumulated ash of a furnace in order to find evidence for illegal fuel use [46].

Also for compressed biomass such as briquettes the proof for using only natural untreated raw material can be provided by meeting the limitations of a fuel standard. For example, in Germany the requirements for wood briquettes concerning heavy metals were fixed according to the standard DIN 51 731 [8]. It requires staying below the following threshold values:

- Arsenic (As) < 0.8 mg/kg
- Cadmium (Cd) < 0.5 mg/kg
- Chrome (Cr) < 8 mg/kg
- Copper (Cu) < 5 mg/kg
- Mercury (Hg) < 0.05 mg/kg
- Lead (Pb) < 10 mg/kg
- Zinc (Zn) < 100 mg/kg

Heavy metals can primarily influence the ash quality, as they largely remain in the combustion residues and can limit their reuse for fertilization purposes. But, the heavy metal concentrations of different ash fractions from a thermochemical process can largely differ. Cadmium, zinc and lead are easier volatilized than other heavy metals. In the flue gas they are thus condensed on fly ash particles during the cooling phase and therefore they are accumulated in these particles (e.g., fabric filters, electrostatic precipitators). By separating the bed ashes from the cyclone or filter ashes for reuse or disposal the pollution risks by fertilization can be controlled and minimized [48].

Some heavy metals can act catalytically in the formation of dioxin and furan (PCDD/F). Copper and iron chloride play a leading role in this process; they serve as source for chlorine. Particularly the Cu^{2+} ions can catalyze the formation of C-Cl bindings and the oxidation of carbon [1].

Technical Combustion Properties

The technical combustion properties of biofuels described below are determining the possibilities and boundaries for thermochemical conversion or they play an important role in this process. Apart from the calorific value, the moisture and ash content as well as the ash-softening behavior of the fuels are here presented and discussed.

Calorific Value

Definition. For the calorific value (heating value) a differentiation between the gross calorific value and the net calorific value is made. Both definitions are given and the differences are discussed.

Definition of net calorific value. The net calorific value (q_{net}) is the specific heat released during complete oxidation of a fuel without regarding the latent heat by condensation of any water vapor in the flue gas (EN 14918 [10]). It is defined as absolute value of the specific heat (enthalpy) of combustion, in joules, for unit mass of the biofuel burned in oxygen at constant pressure or at constant volume under such conditions that all the water of the reaction products remains as water vapor (hypothetically at a pressure of 0.1 MPa). If the latent heat of the water vapor would be recovered the released heat would be slightly higher. Therefore the net calorific value was formerly been named as "lower calorific value."

Definition of gross calorific value. Opposite to the net calorific value the gross calorific value (q_{gr}) is the specific heat released at complete oxidation of a fuel when the latent heat by condensation of any water vapor in the flue gas is regarded and utilized. In order to do this the flue gas has to be cooled to condense the water vapor. According to the method for determination (EN 14918 [10]) the reference temperature is here set to 25°C. Compared to the net calorific value the heat yield is higher. Therefore, the gross calorific value was formerly named as "higher calorific value."

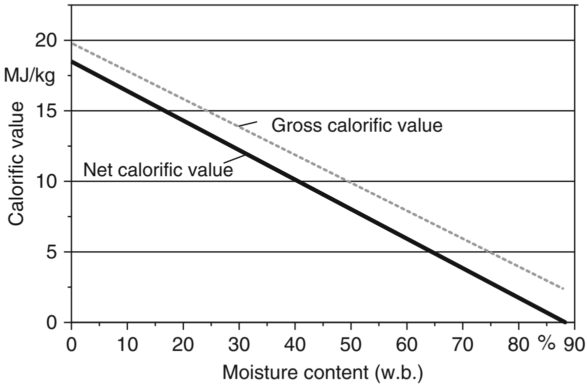
Difference between gross and net calorific value. The water vapor which is formed during the thermochemical reaction and which is the main reason for the two different definitions of the calorific value is either produced in the chemical reaction of the fuel-bound hydrogen or from the free water in the solid biofuel. For each percentage point of hydrogen content in the dry matter, a latent heat of 218.3 J (related to 1 g of fuel) can be calculated (at 25°C flue gas temperature). For the free and bound water in the biomass, the specific latent heat yield per percentage point of moisture content is 24.43 J, related to 1 g fuel mass.

With these specific values, the deviation between gross and net calorific value can be calculated. The terms can therefore not be used alternatively. For the calculation of the chemically bound fuel energy in a given fuel mass, the net calorific value represents the commonly used parameter. This is because in a heating plant the latent heat via flue gas condensation can only be used if the heat use system is designed for low temperature levels. Furthermore, the combustion unit itself and the chimney system must be able to manage the produced condensates without damage (e.g., condensing boilers). These circumstances are however rarely given. The common use of the net calorific value is therefore a technical convention, which regards the currently given practice of solid fuel conversion systems. This agreement however leads to the paradox, that conversion plants, where the respective technical infrastructure for flue gas condensation and low temperature heat use is given, can thus achieve efficiencies of more than 100% [33]. If the fuel input would be calculated by using then gross calorific value the efficiency would always be below 100%.

The gross calorific value (q_{gr}) of biomass fuels is usually about 6% (bark), 7% (wood), or 7.5% (herbaceous fuels) higher than the net calorific value (q_{net}) (Table 6). This, however, only applies to absolutely dry biomass fuels. For wet fuels this relative difference between the two parameters increases, because the possible heat yield through re-condensation of the produced water vapor is respectively higher (Fig. 8).

Determination. The determination of the gross calorific value – from which afterwards the net calorific value is calculated – is done by the calorimetric method according to EN/TS 14918 [10]. It consists of two separate tests: (1) the combustion of the calibration substance (benzoic acid) and (2) the combustion of the fuel sample itself. For both combustion tests, the same conditions have to be guaranteed.

The determination of the gross calorific value is done by performing a combustion reaction (in pure oxygen under high pressure) after which the combustion products are in defined conditions. This happens in a so-called calorimetric bomb enclosed by a water



Solid Biofuels, Fuels and Their Characteristics. Figure 8 Difference between gross and net calorific value at variable fuel moisture contents jacket at temperatures of about 25°C (bomb calorimeter). In the water jacket the temperature change can be determined. It represents the released heat during the performed combustion.

After having determined the gross calorific value, the net calorific value is calculated. This is done by reducing the energy content according to the above given correction factors for each percentage point of hydrogen content. In addition, for moisture content a correction is needed by using the above given correction factors. Both corrections account for the heat by condensation usually not recovered (see above). Therefore, an analysis of the hydrogen and the moisture content of the test sample are always needed for the determination of calorific value. Furthermore, the content of oxygen, sulfur, and nitrogen in the fuel is required.

Calorific value of *dry fuels.* For solid biofuels the net calorific value (q_{net}) of the absolutely dry matter is between 16.5 and 19 MJ/kg (Table 6). In practice the rule of thumb applies, it say that about 2.5 kg of air-dried wood represents about 1 l of heating oil (≈10 kWh or ≈36 MJ). For coniferous wood approximately 2% higher net calorific value is observed compared to wood from broad leaf trees [31]. This increase is due to the higher lignin content. For bark from coniferous, another 2% increase is given due to the content of extractives (e.g., resin, oils, and fats). Both component groups are characterized by a relatively high partial calorific value (27.0 and 35.9 MJ/kg), compared to cellulose (about 17.3 MJ/kg) or hemicellulose (about ca. 16.2 MJ/kg) [42].

Wood fuels show a mean increase of net calorific value of about 9% compared to herbaceous fuels. It varies between 16.5 and 17.5 MJ/kg (Fig. 7). Marked differences between grain straw and grain kernels are not given, this also applies to the different grass species. Oil containing fuels (e.g., rapeseed kernels, rapeseed press cake) have a higher calorific value, depending on the individual oil content. This is due to the high calorific value of the oil, which is around 36 MJ/kg (see Table 6).

The calorific value of dry biomass fuels is mainly depending on the content of oxidizable elements (primarily carbon and hydrogen). Additional heat is also released by the oxidation of several main nutrient elements such as sulfur and nitrogen. Due to the usually low contents of these elements, the calorific value of solid biofuels is not influenced significantly. The oxygen content, however, reduces the calorific value because the oxidizable components of oxygen-containing compounds are already available at a higher oxidation state and thus any further oxidation can only provide limited heat yields.

Because of the above interrelation, the net calorific value can be estimated from the knowledge of the elemental composition. This is frequently done by using Eq. 1 (approximation according to BOIE [44]). For biomass, this equation was found best fitting in empirical studies [31]. The net calorific value of dry biomass fuels ($q_{\text{net, d}}$) in MJ/kg is thus calculated from the element content of carbon (C), hydrogen (H), and the main nutrients sulfur (S) and nitrogen (N). Additionally, the oxygen (O) content in percent of the dry matter is required. When using Eq. 1 a mean error of 4% is given [31]:

$$\left(q_{\text{net, d}}\right) = 34.8\text{C} + 93.9\text{H} + 10.5\text{S} + 6.3\text{N} - 10.8\text{O} \tag{1}$$

Recently also a new biomass specific estimation for the gross calorific value (dry basis) was derived from 122 data sets [23]. This estimation is given in Eq. 2.

$$\begin{aligned}\left(q_{\text{gross, d}}\right) = {} & 1.87\text{C}^2 - 144\text{C} - 2.802\text{H} \\ & + 63.8\text{CH} + 129\text{N} + 20.147\end{aligned} \tag{2}$$

$q_{\text{gross, d}}$ in kJ/kg is given when for carbon (C), hydrogen (H), and nitrogen (N) the values are entered in mass-% from the elementary analyses of the dry biomass fuel.

Impact of moisture content. The highest influence on the net calorific value of a biomass is given by the moisture content. Because moisture content is highly variable, comparisons between fuel types are always made on dry matter basis. Between moisture content and actual calorific value, a linear correlation is given (Fig. 8).

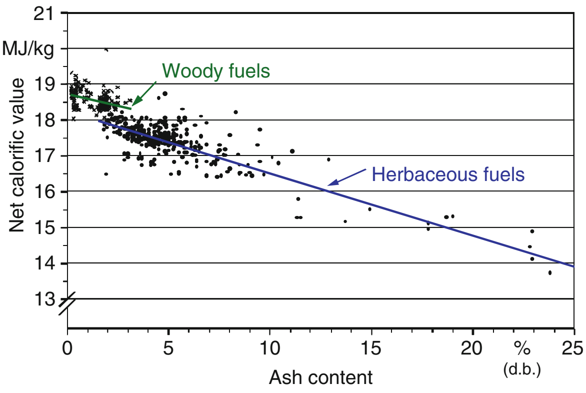
For an estimation of the actual amount of energy, the net calorific value as given at moisture content upon delivery or energetic use is relevant. The respective calculation is done using Eq. 3. $q_{\text{net, ar}}$ is the net calorific value of the biomass as received (in MJ/kg), M is the given moisture content (in %), $q_{\text{net, d}}$ is the calorific value of the dry biomass, and the constant

2.443 results from the evaporation heat of water (in MJ/kg), at a temperature of 25°C.

$$q_{\mathrm{net,\,ar}} = \frac{q_{\mathrm{net,\,d}}(100 - M) - 2.443M}{100} \tag{3}$$

Impact of ash content. The ash content is an influencing factor, too. This, for example, becomes visible when regarding the reduced net calorific value of sunflower straw and grass cuttings from roadsides compared to wood (Table 6). Figure 9 demonstrates this dependency. The usually limited bandwidth of ash content in the fuels leads to a relatively low impact in calorific value. Only if heavy secondary pollution with minerals occur (e.g., for roadside grass cuttings) this can be different.

Estimating an amount of energy. On the basis of the calorific value and the moisture content of the fuel the amount of energy of a given batch can be calculated. To do this the mass has to be determined. For wood logs, which are mainly traded by the volume (stacked cubic meter) a rough estimation of the mass can be made via conversion into solid cubic meters (massive wood), for example by using the conversion factors given in Table 10. From the solid cubic meters the total wood mass can be calculated, this is done by using mean values for the wood density (Table 11). Because in nature wood is not available at absolutely dry stage the wood densities at given moisture content should be applied. For three different wood types, this conversion is made in Table 4 for several assortments [29].



Solid Biofuels, Fuels and Their Characteristics. Figure 9
Net calorific value as a function of the ash content of wood and herbaceous fuels (related to dry basis) [31]

The conversions for wood logs was performed using uniform factors (1 solid m^3 = 0.65 stacked m^3 wood logs or 1 solid m^3 = 2.43 m^3 wood chips).

The estimation of an amount of energy of a given batch is finally calculated from the determined (or estimated) mass (Table 4), multiplied by the net calorific value of a respective biomass type at the given moisture content (Eq. 3). In Table 5 some planning figures are given for typical biomass fuels and assortments. In order to convert from mega-joule (MJ) into kilowatt hours (kWh) a division by 3.6 is made. One liter of heating oil equivalent (light heating oil) is calculated by dividing the energy content given in kWh by 10 (10 kWh ≈ 1 l heating oil).

The increase of the available fuel energy by drying is usually overestimated. It is fact that the reduction of moisture content leads to a linear increase of the net calorific value (Fig. 8). However, this parameter is related to the fuel mass with water. Thus the drying also reduces the total fuel mass of a given batch. Therefore, the energy increase by drying is not proportional to the increasing net calorific value (as received).

Figure 10 shows the actual impact of drying on the fuel energy of a given cubic meter of stacked or poured bulk material. For example, the drying of spruce wood logs (1 m^3) from 50% to 15% moisture content leads to an fuel energy increase of 135 kWh, this is equivalent to 13% (see variant B in Fig. 10, left figure). For wood chips, e.g., 1 m^3 spruce wood chips, the energy content of freshly harvested material at 50% moisture content increases by 85 kWh if the fuel is dried down to 15% moisture content (i.e., 13% increase, see variant B in Fig. 10, right figure). If, however, air-dried material is assessed the shrinkage has mostly already happened. Then the valuation of the fuel energy in a given cubic meter of stacked or bulk fuel follows variant A in Fig. 10.

Consequently, the drying of biomass fuels can only lead to significant energy increases if the starting point of drying is at high moisture content. At lower moisture content, the drying mainly improves fuel quality and minimizes fuel losses by biological processes during storage. However, drying is often also a requirement to achieve higher combustion temperatures, which can lead to improved burnout (mainly for residential furnaces). For some thermochemical processes drying is even essential (e.g., log wood stoves or updraft gasification).

Solid Biofuels, Fuels and Their Characteristics. Table 4 Mass of various volume assortments and wood types as a function of moisture content. Solid: solid cubic meter; log: wood logs 33 cm stacked; chips: wood chips; sm^3: solid cubic meter

Moisture content in %	Beech			Spruce			Pine		
	solid 1 m^3	log 1 sm^3	chips 1 m^3	solid 1 m^3	log 1 sm^3	chips 1 m^3	solid 1 m^3	log 1 sm^3	chips 1 m^3
	Mass per unit[a] *in kg*								
0	680	422	280	430	277	177	490	316	202
10	704	437	290	457	295	188	514	332	212
15	716	445	295	472	304	194	527	340	217
20	730	453	300	*488*	315	201	541	349	223
30	798	495	328	541	349	223	615	397	253
40	930	578	383	631	407	260	718	463	295
50	1,117	694	459	758	489	312	861	556	354

[a] Regarding the fact that wood looses volume while drying; the dry matter densities used here (at 0% moisture) are representing the particle density of dried wood according to Table 11. The respective wood density (incl. moisture) was corrected by the maximum shrinkage (beech 17.9%, spruce 11.9%, pine 12.1%). Between the dry matter density and the density at fiber saturation point (moisture content of 25%, 25% and 21% for beech, spruce, and pine, respectively, see [41]) a linear volume change is assumed

Volatile Matter

All products released from the dry organic substance during pyrolytic decomposition under defined heating conditions are volatile matter. Depending on the fuel type, this fraction is variable. Thus, it is a useful parameter to characterize the fuel's ability to disintegrate into combustible gaseous compounds under heat impact.

The volatile matter content is not an absolute figure. It was defined through convention. It is determined under standardized conditions following EN 15148 [16]. A test portion is heated without contact to ambient air at 900°C ± 10°C for 7 min. The percentage of volatile matter is calculated from the loss in mass of the test portion after deducting the loss in mass due to moisture. In order to achieve a reproducible measurement, the end temperature and the total time of the test have to be monitored carefully. Furthermore, the access to air is to be prevented in order to avoid oxidation.

The volatile matter content allows conclusions on the flame length during combustion or on the gas build-up in gasification. It is thus a relevant characteristic for furnace construction. For example, it can be necessary to increase the amount of secondary air flow if the fuel has high volatile matter content. Also, the combustion space in the furnace has to be larger for high volatile matter contents in order to ensure a sufficiently high residence time of the larger gas volume released.

For lignocellulose fuels, the volatile matter content in the total dry mass is between 74% and 83%. The upper end of this bandwidth is marked by wood fuels (around 82% volatile matter) while for grain straw and grassland cuttings lower values of 74% and 76% are reported (Table 6). In coal the volatile matter is significantly lower. For hard coal a range of 6–45% and for lignite values between 45% and 63% are reported.

Moisture Content

The moisture content is the share of water which can be removed from the fuel under defined conditions. It is usually related to the total mass including water. Sometimes it is also related to the dry matter (e.g., in Germany it is then denominated as "wood moisture" instead of "moisture content"; this term is common in forestry and wood processing industry). However, for energy purposes the moisture content (based on the total mass) is internationally more commonly used [9].

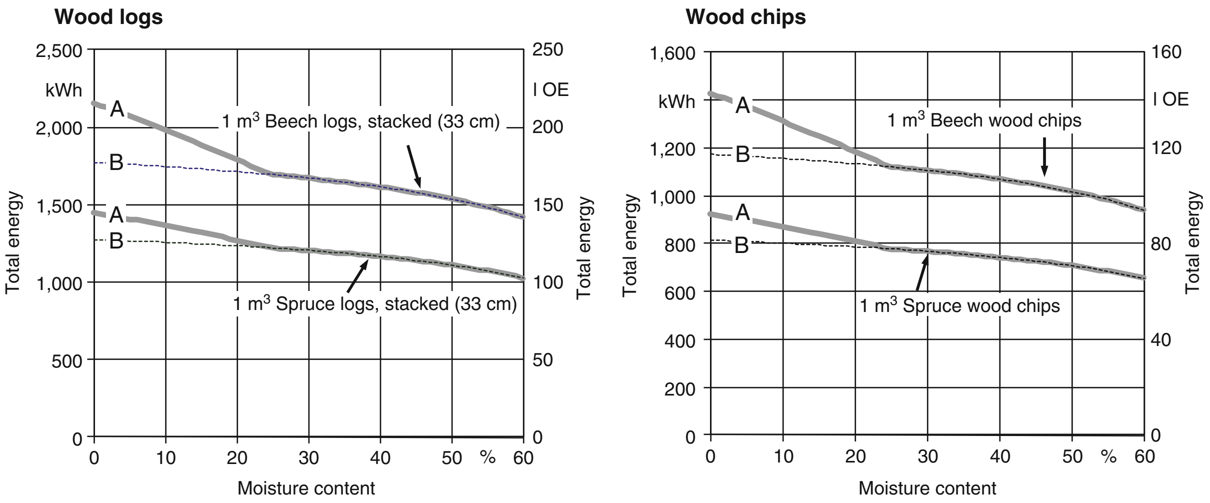
Solid Biofuels, Fuels and Their Characteristics. Table 5 Planning figures for the evaluation of the energy content in a given fuel batch (for wood logs and wood chips the volume change which happens below 25% moisture content was considered) (*OE* oil equivalent, based on light heating oil)

Fuel	Unit	Moisture content *M* in %	Mass (at *M*) in kg	Net calorific value (at *M*) in MJ/kg	Fuel value		
					in MJ	in kWh	in l OE
Wood logs, stacked							
Beech 33 cm, dry	1 sm^3	15	445	15.3	6,797	1,888	189
Beech 33 cm, skin-dry	1 sm^3	30	495	12.1	6,018	1,672	167
Spruce 33 cm, dry	1 sm^3	15	304	15.6	4,753	1,320	132
Spruce 33 cm, skin-dry	1 sm^3	30	349	12.4	4,339	1,205	121
Wood chips							
Beech, dry	1 m^3	15	295	15.3	4,503	1,251	125
Beech, skin-dry	1 m^3	30	328	12.1	3,987	1,107	111
Spruce, dry	1 m^3	15	194	15.6	3,032	842	84
Spruce, skin-dry	1 m^3	30	223	12.4	2,768	769	77
Pellets							
Wood pellets, by volume	1 m^3	8	650	17.1	11,115	3,088	309
Wood pellets, by weight	1 t	8	1,000	17.1	17,101	4,750	475
Fuels by weight							
Beech, dry	1 t	15	1,000	15.3	15,274	4,243	424
Beech, skin dry	1 t	30	1,000	12.1	12,148	3,374	337
Spruce, dry	1 t	15	1,000	15.6	15,614	4,337	434
Spruce, skin dry	1 t	30	1,000	12.4	12,428	3,452	345
Herbaceous (e.g., straw)	1 t	15	1,000	14.3	14,254	3,959	396

It is determined by placing a sample in a drying cabinet at 105°C until constant mass (i.e., drying until no further mass differences can be recorded). This procedure follows the European Standard EN 14774-1 [22].

Natural untreated biomass fuels can also contain some small amount of highly volatile extractives with high-energy content (section "Molecular Composition"). These substances can become volatile during the moisture content determination in a drying cabinet. They are mostly α-pinenes. However, the difference in the measured moisture content is usually below 1%. Only for oil containing materials (e.g., rapeseed press cake) slightly higher deviations are observed when drying is performed at 80°C instead of the usual 105°C [52]. For vast majority of solid biomass fuels the possible error by accepting any volatilization of non-water substances can be neglected in the assessment of a given fuel (e.g., for the determination of the calorific value).

Higher measuring errors are however possible if – as it is realized in practice – rapid methods are applied for moisture content determination. This applies particularly to measuring devices operating according to the electrical conductivity principle as used for wood logs. They usually underestimate the actual moisture content [51]. Rapid test methods for wood chips using capacitance or infrared-reflection methods (NIR) are significantly more accurate. Their measuring inaccuracy is around 3–10% and it remains constant over a large range of moisture contents up to 50% [2, 62].



Solid Biofuels, Fuels and Their Characteristics. Figure 10
Energy content in a stacked cubic meter of wood logs (*left figure*) or in a cubic meter of wood chips (*right figure*) as a function of fuel moisture content. Variant A and B: with and without regarding volume changes by swelling and shrinkage (i.e., for variant A the shrinkage volume is replaced while for variant B the dry matter content remains the same) (*OE* oil equivalent, for light heating oil)

Any false estimation of the moisture content affects the valuation of the fuel energy; this is because the moisture content is the major determinant for the net calorific value at the given drying stage. In nature, totally dry biomass material is not available. Thus the remaining moisture content has to be evaporated during thermochemical conversion. The required energy for this process is obtained from the released process heat and thus it reduces the net energy yield if – as it is common – no condensation of the water vapor in the flue gas is performed.

This impact of moisture content on the net calorific value of the biomass (as received) is shown in Eq. 3. Figure 8 illustrates the described function (section “Calorific Value”). It shows that the net calorific value of wood (here: 18.5 MJ/kg) deceases linearly with rising moisture content. At around 88% moisture content the net calorific value is zero.

In the lower moisture range, an effect on volume of wood is given (section “Physical-Mechanical Properties”). Nevertheless, moisture mainly affects the fuel mass and the combustion temperatures to be achieved under adiabatic conditions. Furthermore, the storability of the fuel is influenced. Moisture content above 16% usually speeds up biological degradation and conversion processes associated with energy losses. Additionally there is an increasing risk of fire due to self-heating and possible self-ignition.

Moisture content of biomass fuels is highly variable, depending on the biomass type, the season and the time between provision and energetic use. The usual bandwidth is between 8% and 65%. Fresh from the forest the moisture content of wood is between 45% and 60%. Hard wood has lower moisture content than soft wood. For coniferous wood, the moisture content is higher in winter when assimilation is low compared to summer [4]. This is not true for broad leaf trees. In short rotation forestry (e.g., poplar, willow) there is an increase of moisture content at the beginning of the vegetation period of 5%-points [31]; this results in higher moisture contents if harvesting is delayed to spring.

Equilibrium moisture content of air-dried wood in Central Europe is given between 10% and 20%, depending on the season. This results in a net calorific value between 14.5 and 16.5 MJ/kg. Herbaceous fuels which are died-off or have been field dried and grain kernels can usually be stored at 15% moisture content. Pellets which follow the European pellet standard EN 14961–2 shall have a maximum moisture content of 10% [18].

Solid Biofuels, Fuels and Their Characteristics. Table 6 Technical combustion properties of untreated natural biomass fuels compared to hard and brown coal (mean values according to [31], for coal: [56])

Biomass fuel	Net calorific value in MJ/kg	Gross calorific value in MJ/kg	Ash content in %	Volatile matter content in %	Ash melting properties		
					DT[a] in °C	HT[a] in °C	FT[b] in °C
Hard coal	29.7[c]		8.3	34.7	1,250		
Brown coal	20.6[c]		5.1	52.1	1,050		
Spruce wood (with bark)	18.8	20.2	0.6	82.9	1,426		1,583
Beech wood (with bark)	18.4	19.7	0.5	84.0			
Poplar (short rotation)	18.5	19.8	1.8	81.2	1,335		1,475
Willow (short rotation)	18.4	19.7	2.0	80.3	1,283		1,490
Bark (coniferous)	19.2	20.4	3.8	77.2	1,440	1,460	1,490
Rye straw	17.4	18.5	4.8	76.4	1,002	1,147	1,188
Wheat straw	17.2	18.5	5.7	77.0	998	1,246	1,302
Triticale straw	17.1	18.3	5.9	75.2	911	1,125	1,167
Barley straw	17.5	18.5	4.8	77.3	980	1,113	1,173
Rapeseed straw	17.1	18.1	6.2	75.8	1,273		1,403
Maize straw	17.7	18.9	6.7	76.8	1,050	1,120	1,140
Sunflower straw	15.8	16.9	12.2	72.7	839	1,178	1,270
Hemp straw	17.0	18.2	4.8	81.4	1,336	1,420	1,456
Rye whole plants	17.7	19.0	4.2	79.1			
Wheat whole plants	17.1	18.7	4.1	77.6	977	1,155	1,207
Triticale whole plants	17.0	18.4	4.4	78.2	833	982	1,019
Rye kernels	17.1	18.4	2.0	80.9	710		810
Wheat kernels	17.0	18.4	2.7	80.0	687	887	933
Triticale kernels	16.9	18.2	2.1	81.0	730	795	840
Rapeseed kernels	26.5		4.6	85.2			
Miscanthus	17.6	19.1	3.9	77.6	973	1,097	1,170
Hay (nature conservation)	17.4	18.9	5.7	75.4	1,061		1,228
Tall fescue	16.4	17.8	8.5	72.0	869	1,197	1,233
Ryegras	16.5	18.0	8.8	74.8			
Gras from roadsides	14.1	15.2	23.1	61.7	1,200	1,270	1,286

[a] *DT* deformation temperature, *HT* hemisphere temperature, *FT* flow temperature (according to CEN/TS 15370-1 [15])

[b] Here: determination acc. to DIN 51 730 [7], deviation to results achieved with newer method are possible

[c] Typical moisture content hard coal: 5%; crude brown coal 50% [56]

Ash Content

The inorganic residue after combustion of a solid biofuels is the ash. It can originate directly from the (unpolluted) fuel or it can be caused by mineral pollutants which have been entrained during the supply chain (e.g., during harvesting, comminution, transport, storage).

The ash content is calculated by the mass of the residue remaining when a sample is heated under defined conditions EN 14775 [20]. This is done by rising the oven temperature over 30–50 min to 250°C and then keeping the temperature constant over 60 min to allow any volatiles to leave the sample before combustion. Then the oven temperature rises at a constant increase of 10 K/min to 550°C, where it remains constant over minimum of 120 min.

In previous test methods (e.g., ISO 1171) the ash determination was performed at a much higher temperature of 815°C, which is still common for coal fuels. The results between the two methods can deviate because at high temperatures inorganic matter can partly become volatile by further oxidation or a release of CO_2 from the disintegration of carbonates can lead to material losses. This systematic deviation can be between zero and several percentage points, depending on the fuel type and ash content level [31].

Of all biomass fuels wood has the lowest ash content in the dry matter (about 0.5%). Higher values are thus usually due to secondary pollution (e.g., by adhering soil). This can be read from the frequency distribution curve for the ash content following a pattern with a peak on the left side (Fig. 7). Accordingly, ash content above 1% is rare for wood alone (without needles or leaves). Only wood from short rotation forestry (e.g., poplar, willow) contains usually higher amounts of ash (about 2%). This is due to the higher bark content of young wood and because bark contains more ash than the heartwood. Bark from spruce, for example, has ash content between 2.5% and 5% (Table 6). The ash content is even higher for most herbaceous fuels.

The ash content of a fuel has an environmental impact and it influences the technical design of a furnace. Higher ash content in the fuel can lead to increased particle emissions or to further requirements for particle separation. Additionally, special technical solutions may be required for the deashing and cleaning of heat exchanger surfaces. Furthermore, the higher efforts for ash handling and disposal are increasing the process costs.

In the ash, several elements described in section "Elemental Composition" are accumulated. These elements are mainly calcium (Ca), magnesium (Mg), potassium (K), phosphorous (P), and sodium (Na). The mean composition of coarse ash from combustion of wood is about 42% CaO, about 6% K_2O, about 6% MgO, about 3% P_2O_5, and about 1% Na_2O. Additionally there is a minor content of iron (Fe) and manganese (Mn). Ashes from straw fuels also have higher shares of K_2O and P_2O_5.

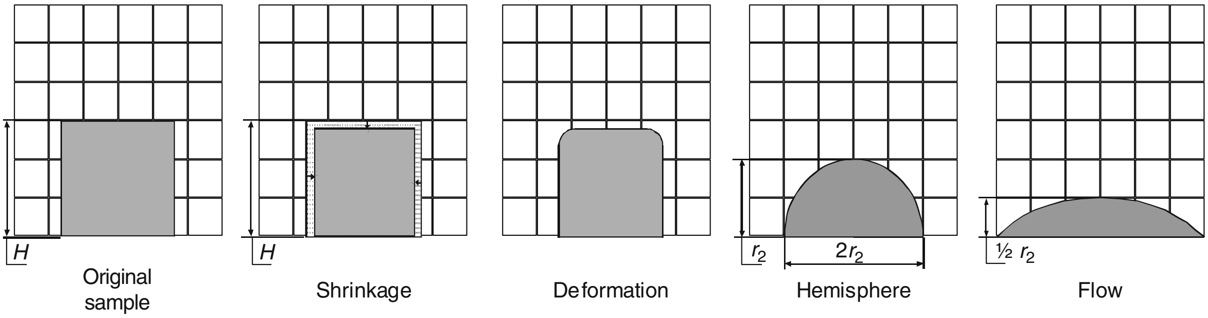
Ash Melting Properties

Due to the induced processes during thermochemical conversion, the physical properties of the ash are modified. Depending on the temperature level, phenomenon like sinterification or even a complete meltdown of ash particles can occur in the fire bed. This can be associated with severe technical disadvantages in the conversion plant and it has to be considered for the design of the combustion process.

The ash melting behavior is depending on the ash constituents and it is thus directly correlated with the fuel composition. Therefore, the ash melting behavior is listed among the fuel-specific properties. As measuring parameters, four characteristic temperatures are used. At these temperatures certain observations concerning ash modifications are made. They are the Shrinkage Starting Temperature (SST), the Deformation Temperature (DT), the Hemisphere Temperature (HT), and the Flow Temperature (FT).

Their determination is done following CEN/TS 15370–1 [15]. A fuel sample is first incinerated according to the principles for the ash content determination (i.e., at 550°C [20]), then the ash is milled and mixed with an additive (water, dextrin, or ethanol) before it is pressed to a sharp edged cylindrical sample piece of 3–5 mm height and the same diameter. The produced test piece is then heated in a defined temperature rise while the observed changes are recorded via a digital camera. The temperatures at which the sample piece is noticeably changing by softening and deformation describe the ash melting behavior. They are defined as follows:

- *Shrinkage starting temperature, SST.* At this temperature the shrinking of the test piece occurs. This temperature is defined as when the area of the test piece falls below 95% of the test piece area at 550°C (Fig. 11). Shrinking may be due to liberation of carbon dioxide, volatile alkali compounds, or sintering. The shrinkage is not always easily detectable but it provides additional information on the



Solid Biofuels, Fuels and Their Characteristics. Figure 11
Characteristic phases during the melting process of a cylindrical ash sample piece according to the standard test method [15] (Original sample = form and size at 550°C; *H* height of sample piece, r_2 radius of hemisphere)

fuel ash behavior. Currently few data are available for shrinkage; Table 6 is therefore incomplete concerning this new parameter.

- *Deformation temperature, DT.* At this temperature the first signs of rounding of the edges due to melting of the test piece occur (Fig. 11).
- *Hemisphere temperature, HT.* It is the temperature at which the test piece forms approximately a hemisphere; this is given when the height becomes equal to half the base diameter (Fig. 11).
- *Flow temperature, FT.* At the flow temperature the ash is spread out over the supporting tile in a layer; the height of this layer is half of the height of the test piece at the hemisphere temperature (Fig. 11).

For fuels with a low ash melting point a high risk of slag deposition and adhesion in the conversion plant is given (e.g., in the combustion chamber, at the grate, on heat exchanger surfaces). Such coatings can lead to blockages, breakdowns, and to an inhibited combustion air supply. They also promote high temperature corrosion. By complex technical attachments, such as water-cooled grates or furnace beds, moving elements in the fire bed, flue gas recirculation, slag breaking elements, fuel turbulence, or fuel additives, the problems can be avoided.

Because wood and bark show high deformation temperatures of about 1,300°C to more than 1,400°C they are usually uncritical in most energetic processes (Table 6). For herbaceous fuels, however, the deformation temperature is almost consistently below 1,200°C. Thus, the described disadvantages bear a technical risk for combustion. For grain straw, for example, a mean deformation temperature of 900–950°C is observed (Fig. 7). However, most critical are grain kernels, where even the flow temperature is usually below 900°C (Table 6).

Similar to the calorific value, the ash deformation temperature is depending on the content of relevant elements. In this context, calcium has a positive impact because it raises the critical temperatures. For potassium, the opposite effect is observed. From these correlations it can be concluded that the ash melting behavior can be improved by mixing the fuel with calcium-containing additives (lime) or by using additives which capture alkaline compounds (e.g., kaolin) [57]. On the other side, the depletion of critical elements from the fuel is a different path for improvements. Therefore the leaching of potassium by precipitation during field-drying or the ripening phase of the crop (e.g., for straw or hay) can have a positive effect under practical conditions. Thus, the ash deformation temperature can be raised in a magnitude of 100–150°C [31].

Physical-Mechanical Properties

Physical-mechanical fuel parameters mainly describe those properties determined during the harvesting and upgrading process. They comprise characteristics such as the surface properties, geometry, size and size distribution, fine matter content, flowing and bridging properties, resistance to abrasion, bulk, and particle density. As for the parameters described in section "Technical Combustion Properties," international standards for their determination are also available for most parameters described here.

In opposite to the fuel composition parameters (section "Fuel Composition"), the technical and physical-mechanical characteristics are largely interacting among each other. The moisture content is also playing a major role in this context of interactions (Fig. 12) and it influences the physical mechanical properties. These parameters are presented and discussed in below.

Shape and Dimensions

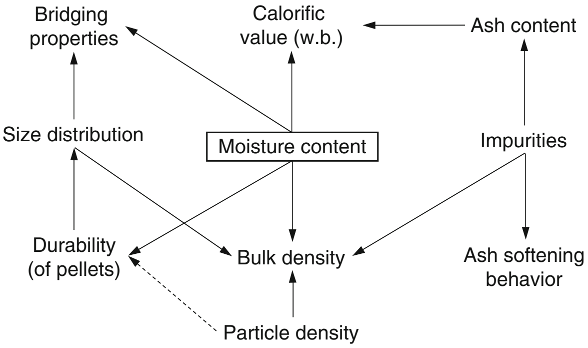
Solid biofuels can be characterized by their shape, which is described by length, height, and width, or by the volume and the geometrical form (i.e., geometric solid).

For hand charged furnaces, specific requirements concerning the maximum fuel expansion are usually given for each furnace type. Firewood can, for example, have a maximum end-user size of 1 m (for meter-wood boilers). But mostly such wood logs are cut one, two, or three times to pieces of 50, 33, or 25 cm in length, depending on the depth of the combustion chamber. Log lengths of 33 cm are here clearly predominant.

For briquettes, produced by mechanical compaction of biomass, variable sizes and shapes are available on the market today. A differentiation between pellets and briquettes is here mainly made by the diameter. From a diameter above 25 mm they are briquettes, below this diameter they are pellets [17].

For pellets European standard size classes are defined:

- Class D06: diameter $\leq$ 6 mm ± 1.0 mm und length (L) $3.15 \leq L \leq 40$ mm
- Class D08: diameter $\leq$ 8 mm ± 1.0 mm und length (L) $3.15 \leq L \leq 40$ mm
- Class D10: diameter $\leq$ 10 mm ± 1.0 mm und length (L) $3.15 \leq L \leq 40$ mm
- Class D12: diameter $\leq$ 12 mm ± 1.0 mm und length (L) $3.15 \leq L \leq 40$ mm
- Class D25: diameter $\leq$ 25 mm ± 1.0 mm und length (L) $10 \leq L \leq 50$ mm



Solid Biofuels, Fuels and Their Characteristics. Figure 12 Interactions between physical-mechanical and technical combustion properties of solid biomass fuels [28]

In addition, herbaceous fuels can be compressed to either round or square bales of variable dimensions (Table 7). Recently also pellets und briquettes are produced. Loose unchopped material is not directly applied as a fuel, but the comminution to chopped material (pieces of 2–40 mm length) can lead to similar mechanization benefits as for wood chips.

Size Classes and Fine Matter

The flow and transport properties of pourable materials are also described by the particle size distribution and the share of fine materials (e.g., by abrasion of pellets). To describe the physical properties of a given wood chip batch, for example, the determination of a mean particle diameter or the mean length alone is not sufficient. Rather the information about the share of certain size classes is needed for proper description. Therefore, a classification using several size classes is useful. Such a system is described in Table 8.

The particle size distribution is relevant for several technical reasons. A larger impact of an unsuitable size distribution is given for mechanical systems in silo emptying, conveying, or charging systems of thermo-chemical conversion plants. Too long particles can, for

Solid Biofuels, Fuels and Their Characteristics. Table 7 Geometry and dimensions of various compressed herbaceous fuels

Fuel form	Geometry	Dimension in cm
Small square bales	Cuboid	40 × 50 × 50–120
Round bales	Cylindrical	Ø 80–200 × 120–170
Big square bales	Cuboid	80–130 × 80–130 × 120–250
Highly compressed fuels: pellets briquettes	Cylindrical, cuboid, etc.	Ø 0.3–2 × variable length variable forms

Solid Biofuels, Fuels and Their Characteristics. Table 8 Requirements for size classes of wood chips according to the European wood chip standard EN 14961-4 [19]

Size class	Minimum 75 wt% in main fraction, mm[a]	Fines fraction, wt % (<3.15 mm)	Coarse fraction, (wt%), max. length of particle (mm), max. cross-sectional area (cm^2)
P16A	$3.15 \leq P \leq 16$ mm	≤12%	$\leq 3\% > 16$ mm, and all < 31.5 mm The cross-sectional area of the oversized particles $<1\ cm^2$
P16B	$3.15 \leq P \leq 16$ mm	≤12%	$\leq 3\% > 45$ mm and all <120 mm The cross-sectional area of the oversized particles $<1\ cm^2$
P31.5	$8 \leq P \leq 31.5$ mm	≤8%	$\leq 6\% > 45$ mm, and all <120 mm The cross-sectional area of the oversized particles $<2\ cm^2$
P45A	$8 \leq P \leq 45$ mm	≤8%	$\leq 6\% > 63$ mm and maximum $3.5\% > 100$ mm, all <120 mm The cross sectional area of the oversized particles $<5\ cm^2$

[a] The numerical values (P-class) for dimension refer to the particle sizes (at least 75 wt%) passing through the mentioned round hole sieve size

example, lead to blockages and damages of the conveyor and they can lower the material throughput. In addition, the flowability and the resistance to air flow during ventilation or drying are affected. Furthermore, the tendency to form a bridge during transhipment (e.g., at the bottom of a silo) is determined by an unsuitable size distribution. Finally, also the possibility for fine material to disintegrate from the bulk (e.g., during transportation) and thus to increase non-uniformity within the fuel bulk is facilitated by an unfavorable size distribution.

The determination of particle size distribution is performed by sieving. This is done using a set of horizontally shaking sieves placed above each other. The particles of a sample are then passed through the screen set starting with the largest hole apertures. Then they are separated according to their size in the respective screen, which is finally weighed. The share of mass in each fraction, assuming that particle density of smaller and larger particles is consistent, then determines the size distribution. For the determination of a particle size distribution according to the European wood chip standard a set of screens with round holes was selected (hole diameters of 3.15, 8, 16, 31.5, 45, and 63 mm). Additionally it can be useful to add a 1 mm (mesh wire sieve) [21].

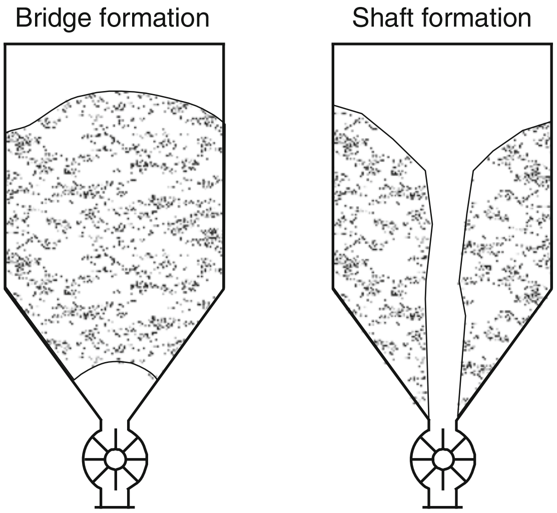
During sieving the particles are rather separated by their width than by their length. Therefore, a considerable amount of particles which are significantly longer than the screen hole aperture width are found in one of the following size class. The median value of a size distribution determined by horizontal screening is therefore mostly only half of the value to be found if the median value was determined from the distribution of the actual lengths (maximum particle expansion) [34]. In particular, higher shares of overlong particles are always determined when the particles largely differ from an ideal sphere shape. This is, for example, the case when the sample is a hog fuel type produced by using blunt tools rather than sharp cutting knifes as applied in wood chip production [34]. Hog fuel usually has a largely higher length-diameter ratio.

Consequently, the classification during sieving is mainly done by sorting according to the maximum particle diameter. However, for the assessment of mechanical fuel properties the results from a size distribution determination by length (i.e., largest expansion) would be the more relevant parameter. This approach would also be more decisive for the mechanical properties of the fuel. But at sufficient accuracy such a measurement can only be performed using continuous image analysis [34]. However, this method is still not widely available. Therefore, the results from a particle size distribution analysis by screening according to EN 15149–1 [21] shall not be interpreted as absolute figures.

During the particle size analysis, the amount of fine material is also determined. It is characterized as the fraction of particles falling through screen hole apertures of about 3.15 or 1.0 mm diameter (internationally inconsistent). The share of fines is often regarded as an independent fuel parameter. This particle fraction is particularly relevant for wood pellets, because dry wood dust can lead to drastic dust formation during pneumatic conveying. It can also increase the risk of explosion by deflagration.

Flowing and Bridging Properties

The fuel extraction from silos and day storages can be inhibited by technical problems created by unfavorable flow properties. The formation of hollow spaces (bridges or arches) or shafts in a silo is possible (Fig. 13). The latter is associated with a core flow of the material instead of the desired mass flow. Both phenomenons finally lead to the problem that the fuel will sooner or later not any more fall downward to the conveyors or the flow becomes unsteady. Frequently there is also an alternating build-up and breakdown of bridges or shafts. Furthermore, the volume of the container is incompletely used and the retention time of the fuel compartments is inhomogeneous. This means that the fuel remains much longer in the dead layers of a shaft silo and this can lead to severe quality losses. The described phenomenons can also be the reason for fuel segregation by particle size, density, and form; a high quality variation is then a consequence.



Solid Biofuels, Fuels and Their Characteristics. Figure 13
Phenomenons of unfavorable flowability of fuels [55]

The problems created by unsuitable flow properties are increasing with the moisture content, the filling depth, and the share of overlong and branched particles while uniform particle sizes and smooth surfaces (e.g., pellets, wood chips without bark) are beneficial [36, 43]. A supplementary sorting to achieve uniform material conditions can thus lead to considerable improvements of the flow properties.

Usual shear cells are not suitable for the determination of flow properties due to the sometimes large particle sizes. Therefore a method for a direct determination of the bridging properties was developed. It uses a special apparatus where a fuel sample of 1.65 m^3 is forced to form a bridge over an opening slot under controlled conditions. The opening width of the slot at the moment when the fuel bridge collapses is taken as a measure for the bridge building properties of the sample. This requires a frictionless opening of the bottom slot. It is achieved by the fact that a flat steel bottom is sliding away underneath a PVC mat on which the fuel sample is resting [36].

Bulk Density

The required storage and transport volume is determined by the bulk density of a pourable fuel or by the stacked density of logs and briquettes. The respective definitions and conversion factors are described below.

Definition. The bulk density is defined as the quotient of the mass of a material filled into a container and the filling volume of the container. The hollow space between the fuel particles is thus not reducing the volume; this also applies to the staked density of wood logs. Typical density values are given in Table 9.

Determination. For determination of the bulk density a sample is being filled in a defined mode into a cylindrical container of 50 l volume (EN 15103 [11]). The container is filled over the edge and is then exposed to controlled shock by dropping it three times from 150 mm height onto a wooden floor. Then the filling volume created by the shock operation is refilled and leveled to the rim of the container. Then the net weight is determined and related to the container volume.

Settling factor. The defined shock exposure operation leads to a certain volume reduction due to compaction effects occurring during the supply chain. These

Solid Biofuels, Fuels and Their Characteristics. Table 9 Typical bulk and staked densities of biomass fuels at a moisture content of 15%

Wood fuels		Density in kg/m^3	Herbaceous fuels		Density in kg/m^3
Wood logs (stacked)	Beech	445	Round bale	Straw	85
	Spruce	305		Hay	100
Wood chips	Soft wood	200	Square bale	Straw, miscanthus	140
				Hay	160
	Hard wood	280		Whole grain crop	190
Wood bark	(coniferous)	175	Chopped	Miscanthus	110
Saw dust		160		Whole grain crop	150
Shavings		90	Grain kernels		750
Wood pellets		650	Pellets		550

compaction effects are mainly due the fact that the fuel is usually transported and/or stored in containers or silos much larger than the measuring container chosen for the method described here. Thus in practice the higher mass load in a storage leads to an increased load pressure and to fuel settling, which can additionally be enhanced by the vibrations during transportation. Furthermore, filling or unloading operations in practice usually apply a higher falling depth than the one chosen for the here performed test. This will also result in a respectively higher compaction due to the increased kinetic energy of the particles falling. The procedure with applying a controlled shock to the sample is thus believed to reflect the practically prevailing bulk density in a better way than a method without shock. This is particularly true when the mass of a delivered fuel has to be estimated from the volume load of a transporting vehicle, which is a common procedure in many countries.

The difference between a measurement with and without shock can be interpreted as the settling factor. The measured results for this factor are given in Fig. 14 for several biomass fuels. It shows that the compaction effect during handling and transhipment is low for wood pellets or grain kernels (only 6–7% settling). However, this effect is largely higher when chopped herbaceous fuel such as Miscanthus is regarded (max. 18% settling). For wood chips the bulk density increase due to controlled shock is around 11%; differences between high or low density wood chips are negligible here (fuels above 180 kg dry matter per m^3 were in Fig. 14 defined as high density fuels).

Transformation to other moisture content bases. For comparability the determined densities should be converted to uniform moisture content or to dry basis. If for practical reasons the swelling and shrinkage is here disregarded, the dry matter based bulk density (D_d) is calculated from the actual bulk density as received (D_{ar}) by regarding the given moisture content (M) according to Eq. 4.

$$D_d = D_{ar} \times \frac{100 - M_{ar}}{100} \tag{4}$$

Equation 4 disregards shrinkage or expansion, which usually cause significant deviations when the sample is measured at different drying stages. For uncompressed wood fuels, these volume changes usually occur at moisture contents below the fiber saturation point, which is at around 25%, depending on the wood species. A true comparison between fuel samples would therefore require a determination at similar moisture contents. Alternatively, a correction factor can be used if sample materials of different moisture content shall be compared and at least one sample is below the fiber saturation point. Here the usual effect of swelling or shrinkage is in the order of around 0.7% volume change per percentage point of moisture difference [32].

Conversion of volumes. In practice, a fuel volume often needs to be converted to another volume basis.

Solid Biofuels, Fuels and Their Characteristics. Table 10 Conversion factors between different wood log assortments (with bark) [37] (sm^3: stacked cubic meter)

Wood type	Solid wood volume in solid m^3	Round wood, stacked in sm^3	1-m logs, split, stacked in sm^3	33-cm logs, split stacked in sm^3	33-cm logs, loose in m^3
For 1 solid cubic meter (with bark)					
Beech	1.00	1.70	1.98	1.61	2.38
Spruce	1.00	1.55	1.80	1.55	2.52
For 1 cubic meter of round wood					
Beech	0.59	1.00	1.17	0.95	1.40
Spruce	0.65	1.00	1.16	1.00	1.63
For 1 cubic meter of 1-m logs (split)					
Beech	0.50	0.86	1.00	0.81	1.20
Spruce	0.56	0.86	1.00	0.86	1.40
For 1 cubic meter of 33-cm logs (split)					
Beech	0.62	1.05	1.23	1.00	1.48
Spruce	0.64	1.00	1.16	1.00	1.62
For 1 cubic meter of 33-cm logs (split)					
Beech	0.42	0.71	0.83	0.68	1.00
Spruce	0.40	0.62	0.72	0.62	1.00

In the untreated state wood is often rated by the solid cubic meter (i.e., without regarding any hollow space). However, when supplied to the final customer as wood logs, the fuel is usually rated as staked or bulk cubic meter. For conversion from solid cubic meters (solid m^3) to staked cubic meters (sm^3) a general factor of 1.43 had in the past widely been used (i.e., 1 solid m^3 is 1.43 sm^3). However, a more differentiated calculation is useful, particularly because the general conversion factor of 1.43 is too low even for very densely piled oven-ready and dry wood logs [37]. Table 10 shows that a staked cubic meter of firewood at 33 cm length is in average produced from 0.62 m^3 of solid beech wood or from 0.64 m^3 of spruce wood. For a single cubic meter of stacked 33 cm-logs a volume of 1.23 sm^3 of 1 m-logs is required. Significantly different conversion factors between spruce and beech wood also observed within the loose logwood assortment (Table 10).

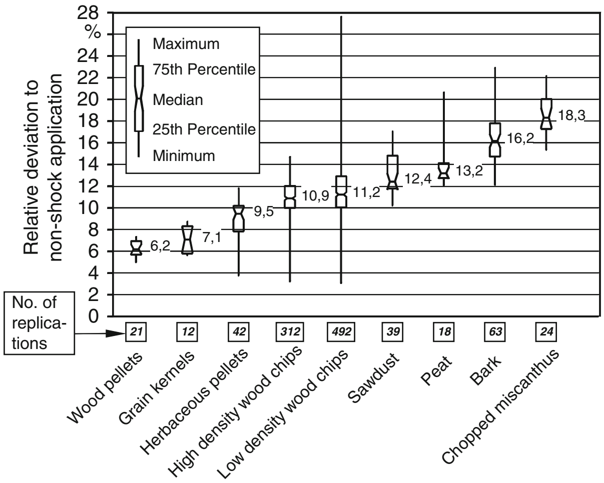
In reality, however, the conversion factors can largely differ from the figures given in Table 10, depending on the processing technology and the physical growth shape of the tree. This applies particularly to the conversion factors from solid to any form of stacked cubic meter.

For wood chips, the conversion from massive (solid) cubic meter to the volume of bulk material is usually done using a general factor [5]. It is:

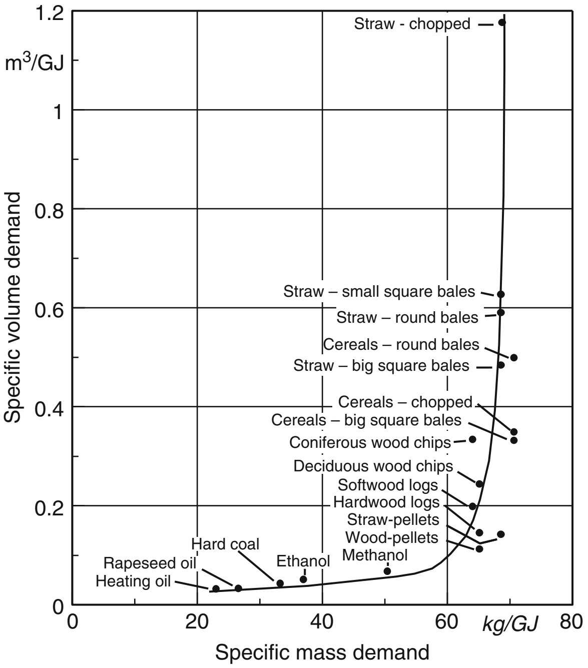
- 1 solid cubic meter (m^3) (massive wood) ≈ 2.43 m^3 wood chips
- 1 stacked cubic meter (sm^3) of stacked wood ≈ 1.7 m^3 wood chips

Larger deviations from this general factor are also likely. But to date no differentiations between wood species or between the applied comminution technologies can yet be made. The shrinkage by drying or the volume losses by shock or vibration (settling factor) can be estimated using the data given in the previous chapters.

Energy density. When assessing biofuels and their specific storage room demand the term “energy density” is sometimes used. It is defined as the respective



Solid Biofuels, Fuels and Their Characteristics. Figure 14 Relative effect of shock impact compared to a non-shock application in bulk density determination ("settling factor") derived from measurements in a 50-l-container, which is dropped three times before refilling, surface leveling and weighing [32]



Solid Biofuels, Fuels and Their Characteristics. Figure 15 Specific mass and storage room demand of different energy sources (for solid fuels a moisture content of 15% is assumed) [26]

mass or volume needed to provide a given unit of fuel energy at a given moisture content. A comparison of selected fuels regarding their energy density is given in Fig. 15.

Particle Density

The particle density of a fuel describes the actual material density (i.e., without regarding the hollow space between the particles). It influences the bulk or stacked density and some combustion properties (e.g., the specific heat transfer rate): Also, the pneumatic transportability is depending on it. Physically the particle density can only be influenced by compaction to pellets or briquettes.

When determining the particle density of compressed biomass fuels (pellets or briquettes), the volume of a single particle is first determined by measuring its buoyancy in a liquid (water with wetting agent) according to EN 15150 [12]. Then the mass as determined in ambient air is set into relation to this volume.

Table 11 shows the particle densities of various wood species given at an absolutely dry stage. When the moisture content of fiber saturation is given (ca. 19–25%) the volume is higher. The difference is the so-called shrinkage factor. This has a respective effect on the particle density of the wetter fuel. The volume change by shrinkage is 17.9% and 12.2% for beech and oak or 11.9% and 12.1% for spruce and pine [41].

The parameter particle density is sometimes used to characterize the intensity and quality of a compaction process. A high particle density indicates a high hardness and thus only little risk of abrasion or fine material losses. However, a significant correlation between particle density and resistance to abrasion has never been clearly observed [58]. For pellets therefore the direct determination of abrasion using a mechanical test method is today preferred (section "Resistance to Abrasion").

Compared to compressed materials the particle density of grain kernels is usually not lower. For oat kernels (with husk), for example, the density is around 1.0 g/cm^3 while wheat kernels without husks have an average density of 1.35 g/cm^3. The density of a grain

Solid Biofuels, Fuels and Their Characteristics. Table 11 Particle density (including shrinkage) of absolutely dry wood [41, 49]

Soft wood (max. 0.55 g/cm^3)		Hard wood (above 0.55 g/cm^3)	
Spruce	0.43 g/cm^3	Oak	0.67 g/cm^3
Fir	0.41 g/cm^3	Sycamore	0.50 g/cm^3
Pine	0.49 g/cm^3	Ash	0.67 g/cm^3
Douglas fir	0.47 g/cm^3	Beech	0.68 g/cm^3
Larch	0.55 g/cm^3	Birch	0.64 g/cm^3
Alder	0.49 g/cm^3	White beech	0.75 g/cm^3
Lime tree	0.49 g/cm^3	Black pine	0.56 g/cm^3
Aspen	0.45 g/cm^3	Hazelnut	0.56 g/cm^3
Poplar	0.41 g/cm^3	Black locust acacia	0.73 g/cm^3
Willow	0.52 g/cm^3	Elm	0.64 g/cm^3

haulm is however significantly lower, for wheat straw it is in average around 0.20 g/cm^3 (considering only wall material) [30].

Resistance to Abrasion

Resistance to abrasion describes the coherence of fuel particles in a compressed material (pellets or briquettes). This property is mainly important for all processes of loading and transhipment, where the material is exposed to mechanical wear, and where small particles are removed and can thus contribute to the release of fine dust. Such dust is usually formed when a silo or storage is pneumatically filled with pellets, because fine wood dust can easily penetrate through small cracks in silos or rooms. With briquettes, an unsuitable mechanical strength can lead to a breaking of the material during hand charging or transport. Moreover, it leads to dirt accumulation near the furnace (e.g., in the living space). A high dust formation can lead to explosion reactions when either a high heat impact or freely flying sparks are given. This can happen in the storage, the feeding system, or within the furnace itself.

For the determination of resistance to abrasion a standard method is applied (EN 15210–1 [13]). A sieved pellet sample is filled into a dust-tight rotating test box of a rectangular geometry (300 × 300 × 125 mm). In the inside, the box is equipped with a baffle. The sample is then exposed to defined mechanical wear by rotating it in the box over 10 min at a speed of 50 rpm. Then the sample is again screened using the previously applied round hole sieve (3.15 mm hole diameter) and the weight difference to the original sample is determined. For high quality pellets, the pellet mass remaining on the screen after the mechanical treatment should be above 97.5%. Such a durability is then classified by "DU97.5" according to the EN 14961–1 [17]. Further quality steps are, for example, DU96.5 and DU95.0 with less remaining mass fraction after the described mechanical treatment and sieving.

For briquettes the mechanical treatment is similar (EN 15210–2 [14]). Instead of the rectangular tumbling chamber, a lying cylinder is used for rotating the sample (diameter and height both being 598 mm). An inbuilt baffle ensures that the sample is exposed to significant mechanical stress over 5 min of rotation at 21 rpm [14]. The applied sample mass of 2 kg is higher because of the larger briquettes.

The stability of pellets or briquettes during mechanical stress depends on several factors. They are, for example, the form (for briquette), the chosen compaction method, or the use of any binding agents. An unsuitable cooling after compaction reduces the mechanical strength. High air humidity during storage can lead to an increased fuel moisture content which also lowers the mechanical stability [28]. The type of material itself also gives a decisive role, because composition and macromolecular structure can influence the effectiveness of the binding forces. Therefore the stability of straw pellets is usually lower than of wood pellets [58].

Future Directions

In some regions, biomass fuels are already becoming scarce. Countries with high ambitions or obligations concerning their future share of renewable energy or CO_2-reduction goals are therefore increasingly depending on imported biomass. In such a scenario, the energetic density is a decisive criterion. Therefore, pelletization of biomass is an increasingly important technical option to realize long-distant trade relations. International standardization in this field is now providing the necessary directions and enables the introduction of sound and comprehensive quality assurance systems.

The growing importance of pelletization does not only apply to wood fuels but also to agricultural residues and non-woody energy crops. However, the scope of using herbaceous fuels is today still limited due to their unfavorable properties. The upcoming search for new resources therefore needs to be associated with developing and applying new methods for fuel improvements. This can, for example, be the application of additives or applying other pretreatment measures before pelletizing. Desirable changes in fuel composition can also be achieved by depleting pollutants through active leaching with water or by thermochemical pretreatment measures such as heat application (torrefaction) or the use of steam and pressure (hydrothermal carbonization). In such cases, largely homogenized high-value fuels are produced and not only their chemical composition but also their physical-mechanical properties are thus adapted to new requirements. This development can enable to establish new technical applications for the fuel (e.g., higher rates of co-combustion with fossil coal).

In general, the now introduced European and ISO-standards for biomass are about to boost possibilities for quality increases and they allow the introduction of high grade market fuels which finally can stimulate technologically and environmentally more sophisticated conversion routes. Nevertheless, in view of the increasing depletion of existing potentials – particularly for low value biomass residues and by-products – the future challenge is to select, improve, and process suitable energy crops, and to monitor all quality relevant influences in order to achieve consistently high biomass fuel quality. However, the knowledge base for such comprehensive quality manipulations is still thin and sound, and predictable technical measures are yet few.

Bibliography

1. Ballschmiter KH, Bacher R (1996) Dioxine – Chemie, Analytik, Vorkommen Umweltverhalten und Toxikologie der halogenierten Dibenzo-p-Dioxine und Dibenzofurane. VHC, Weinheim
2. Böhm T, Hartmann H (2000) Wassergehalt von Holzhackschnitzeln – Ein Vergleich der Bestimmungsmethoden. Landtechnik 55(4):280–281
3. Brunner T (2006) Aerosol and coarse fly ashes in fixed-bed biomass combustion. Dissertation an der Eindhoven University of Technology (Faculty of Mechanical Engineering), The Netherlands, Eigenverlag
4. Burmester A (1980) Holzfeuchtigkeit in Nadelhölzern – Jahreszeitliche Einflüsse auf die Eigenschaften des Splint- und Kernholzes von Nadelbäumen. Holz Zentralbl 106(91): 1303–1304
5. Centrale Marketinggesellschaft der deutschen Agrarwirtschaft (Hrsg.) (1988) Holz als Energierohstoff; Centrale Marketinggesellschaft der deutschen Agrarwirtschaft, Selbstverlag, Bonn, 2 Auflage
6. Daugbjerg Jensen P, Hartmann H, Böhm T, Temmerman M, Rabier F, Morsing M (2006) Moisture content determination in solid biofuels by dielectric and NIR reflection methods. Biomass Bioenergy 30:935–943
7. Deutsches Institut für Normung (Hrsg.) (1984) DIN 51 730 (Prüfung fester Brennstoffe – Bestimmung des Ascheschmelzverhaltens). Beuth, Berlin
8. Deutsches Institut für Normung (Hrsg.) (1996) DIN 51 731 Prüfung fester Brennstoffe – Presslinge aus naturbelassenem Holz – Anforderungen und Prüfung. Beuth, Berlin
9. Deutsches Institut für Normung (Hrsg.) (2003) CEN/TS 14588:2003: Feste Biobrennstoffe – Terminologie, Definitionen und Beschreibungen. Beuth, Berlin
10. Deutsches Institut für Normung (Hrsg.) (2005) CEN/TS 14918:2005: Feste Biobrennstoffe – Verfahren zur Bestimmung des Heizwertes. Beuth, Berlin
11. Deutsches Institut für Normung (Hrsg.) (2005) FprEN 15103:2009: Solid biofuels – determination of bulk density. Beuth, Berlin
12. Deutsches Institut für Normung (Hrsg.) (2005) prCEN/TS 15150:2005: Solid biofuels – methods for the determination of particle density. Beuth, Berlin
13. Deutsches Institut für Normung (Hrsg.) (2005) prCEN/TS 15210-1:2005: Feste Biobrennstoffe – Verfahren zur Bestimmung mechanischen Festigkeit – Teil 1 – Pellets. Beuth, Berlin
14. Deutsches Institut für Normung (Hrsg.) (2005) CEN/TS 15210-2:2005 Feste Biobrennstoffe – Verfahren zur Bestimmung mechanischen Festigkeit – Teil 2 – Briketts. Beuth, Berlin
15. Deutsches Institut für Normung (Hrsg.) (2006) CEN/TS 15370-1:2006 Solid biofuels – method for the determination of ash melting behaviour – Part 1: characteristic temperatures method. Beuth, Berlin
16. Deutsches Institut für Normung (Hrsg.) (2009) CEN/TS 15148:2005: Solid biofuels – solid biofuels – determination of the content of volatile matter, Final draft, April 2009. Beuth, Berlin
17. Deutsches Institut für Normung (Hrsg.) (2010) EN 14961-1:2010: Solid biofuels –fuel specifications and classes – Part 1: general requirements. Beuth Verlag, Berlin
18. Deutsches Institut für Normung (Hrsg.) (2010) EN 14961-2:2010: Solid biofuels – fuel specifications and classes – Part 2: wood pellets for non-industrial use. Beuth Verlag, Berlin

19. Deutsches Institut für Normung (Hrsg.) (2010) FprEN 14961-4:2010: Solid biofuels – fuel specifications and classes – Part 4: wood chips for non-industrial use. Beuth Verlag, Berlin
20. Deutsches Institut für Normung (Hrsg.) (2010) EN 14775: 2009: Solid biofuels – determination of ash content. Beuth, Berlin
21. Deutsches Institut für Normung (Hrsg.) (2010) FprEN/TS 15149-1:2010: Solid biofuels – determination of particle size distribution – Part 1: oscillating screen method using sieve apertures of 1 mm and above. Beuth, Berlin
22. Deutsches Institut für Normung (Hrsg.) EN 14774:2010 (2010): Solid biofuels – determination of moisture content – oven dry method – Parts 1 to 3. Beuth, Berlin
23. Friedl A et al (2005) Prediction of heating value of biomass fuel from elemental composition. Anal Chem 554:191–198
24. Gammel R (1989) Forstbenutzung – Technologie, Verwertung und Verwendung des Holzes. Verlag Paul Parey, Hamburg, Pareys Studientexte 67, 193S
25. Griffin RD (1986) A new theory of dioxin formation in municipal solid waste combustion. Chemosphere 9–12: 1987–1990
26. Hartmann H (1996) Analyse und Bewertung der Systeme zur Hochdruckverdichtung von Halmgut; Bayerisches Staatsministerium für Ernährung, Landwirtschaft und Forsten (Hrsg.), Selbstverlag, München, Reihe “Gelbes Heft” 60
27. Hartmann H (1998) Influences on the quality of solid biofuels – causes for variations and measures for improvement. In: Biomass for energy and industry, proceedings of the 10th European conference and technology exhibition, Würzburg, 8–11 June 1998. C.A.R.M.E.N in Würzburg-Rimpar, Germany, pp 184–187
28. Hartmann H (2004) Physical-mechanical fuel properties – significance and impacts. In: Hein M, Kaltschmitt M (eds) Standardisation of solid biofuels – international conference, 6–7 Oct 2004. Institute for Energy and Environment (IE), Leipzig, pp 106–S115
29. Hartmann H (Hrsg.) (2007) Handbuch Bioenergie-Kleinanlagen (2. vollst. überarbeitete -Auflage). Sonderpublikation des Bundesministeriums für Verbraucherschutz, Ernährung und Landwirtschaft (BMVEL) und der Fachagentur Nachwachsende Rohstoffe (FNR), Gülzow, 224 S
30. Hartmann H, Böhm T (2000) Messverfahren zur Bestimmung der Rohdichte von biogenen Festbrennstoffen. Bayerische Landesanstalt für Landtechnik, Freising, (noch unveröffentlicht)
31. Hartmann H, Böhm T, Maier L (2000) Naturbelassene biogene Festbrennstoffe – Umweltrelevante Eigenschaften und Einflussmöglichkeiten. Bayerisches Staatsministerium für Landesentwicklung und Umweltfragen (Hrsg.), München, Reihe “Materialien”, 154 Download
32. Hartmann H, Böhm T, Daugbjerg Jensen P, Temmerman M, Rabier F, Jirjis R, Hersener J-L, Rathbauer J (2004) Methods for bulk density determination of solid biofuels. In: Van Swaaij WPM, Fjällström T, Helm P, Grassi A (Hrsg.) 2nd world conference and technology exhibition on biomass for energy, industry and climate protection, Rome, 10–14 May 2004. Energy research Centre of the Netherlands ECN, Petten, pp 662–665
33. Hartmann H, Roßmann P, Link H, Marks A, Müller R, Amann E (2004) Secondary flue gas condensation for domestic wood chip boilers. In: Van Swaaij WPM, Fjällström T, Helm P, Grassi A (Hrsg.) 2nd world conference and technology exhibition on biomass for energy, industry and climate protection, Rome, 10–14 May 2004. Energy research Centre of the Netherlands ECN, Petten, pp 1334–1337
34. Hartmann H, Böhm T, Daugbjerg Jensen P, Temmerman M, Rabier F, Golser M (2006) Methods for size classification of wood chips. Biomass Bioenergy 30:944–953
35. Hartmann H, Turowski P, Roßmann P, Ellner-Schuberth F, Hopf N (2007) Grain and straw combustion in domestic furnaces – influences of fuel types and fuel pretreatment. In: Maniatis K, Grimm H-P, Helm P, Grassi A (eds) Proceedings 15th European biomass conference and exhibition, Berlin, Germany, 7–11 May 2007. ETA Renewable Energies, Florence, Italy, pp 1564–1569
36. Hinterreiter S, Hartmann H, Turowski P, Kallio M, Lazdiņš A, Zimelis A, Rathbauer J, Sulzbacher L, Sønderstgaard Sørensen K, Temmerman M (2010) Determination of bridging properties – experimental and model approach. In: ETA Renewable Energies (eds) Proceedings 18th European biomass conference and exhibition – from research to industry and markets. Lyon, France, 03–07 May 2010. ETA Renewable Energies, Florence, Italy, pp 1688–1698
37. Höldrich A, Hartmann H, Decker T, Reisinger K, Schardt M, Sommer W, Wittkopf S, Ohrner G (2006) Rationelle Scheitholzbereitstellungsverfahren. Berichte aus dem TFZ, 11, Technologie- und Förderzentrum (TFZ), Selbstverlag, Straubing, 274 S. www.tfz.bayern.de
38. Huber S, Friess H (1998) Emissions of biomass combustion plants. In: Kopetz Hua (Hrsg.) Biomass for energy and industry. C.A.R.M.E.N., Würzburg-Rimpar, pp 1405–1408
39. Launhardt T, Hartmann H, Link H, Schmid V (2000) Verbrennungsversuche mit naturbelassenen biogenen Festbrennstoffen in einer Kleinfeuerungsanlage – Emissionen und Aschequalität. Bayerisches Staatsministerium für Landesentwicklung und Umweltfragen (Hrsg.), München, Reihe “Materialien”, 156
40. Lee D, Owens VN, Boe A, Jeranyama P (2007) Composition of herbaceous biomass feedstocks. North Central Sun Grant Center (Hrsg.), South Dakota State University, Selbstverlag, Brookings, 16 S
41. Lohmann U (1993) Handbuch Holz, DRW-Verlag, Stuttgart, 4. Auflage, 312 S
42. Marutzky R (1993) Moderne Holzfeuerungsanlagen. Centrale Marketinggesellschaft der deutschen Agrarwirtschaft (Hrsg.), Selbstverlag, Bonn
43. Mattsson JE (1990) Basic handling characteristics of wood fuel: angle of repose, friction against surfaces and tendency to bridge building for different assortments. Scand J Forest Res 5:583–597

44. Netz H (1982) Verbrennung und Gasgewinnung bei Festbrennstoffen; Technischer Verlag Resch, München
45. Nimz H (1974) Beech lignin-proposal of a constitutional lignin. Angew Chem Int Edit 13:313–321
46. Noger D, Pletscher E (1998) Brennstoffkriminalität – Schnelltest. In: Siebtes symposium Biobrennstoffe und umweltfreundliche Energietechnik, November 1998; OTTI-Technologie Kolleg, Selbstverlag, Regensburg, pp 173–180
47. Nultsch W (1982) Angewandte Botanik. Thieme, Stuttgart, 7. Auflage
48. Obernberger I (1997) Nutzung fester Biomasse in Verbrennungsanlagen unter besonderer Berücksichtigung des Verhaltens aschebildender Elemente; Schriftenreihe Thermische Biomassenutzung (1), dbv, Graz, p 349
49. Österreichisches Normungsinstitut (Hrsg.) (1998) ÖNORM M7132 Energiewirtschaftliche Nutzung von Holz und Rinde als Brennstoff – Begriffsbestimmungen und brennstofftechnologische Merkmale; Selbstverlag, Wien
50. Rau JA (1989) Composition and size distribution of residential wood smoke particles. J Aerosol Sci Tech 10:181–192
51. Reisinger K, Hartmann H, Turowski P, Nürnberger K (2009) Schnellbestimmung des Wassergehaltes im Holzscheit – Vergleich marktgängiger Messgeräte. Berichte aus dem TFZ 16. Eigenverlag Technologie- und Förderzentrum, Straubing 2009, p 110. www.tfz.bayern.de
52. Samuelsson R, Burvall J, Jirjis R (2006) Comparison of different methods for the determination of moisture content in biomass. Biomass Bioenergy 30:929–934
53. Sander B (1996) Fuel data for Danish biofuels and improvement of the quality of straw and whole crops. In: Chartier P (ed) Biomass for energy and the environment. Elsevier Science, Oxford, pp 490–495
54. Sander M-L, Ericsson T (1998) Vertical distributions of plant nutrients and heavy metals in salix viminalis stems and their implications for sampling. Biomass Bioenergy 14(1):57–66
55. Schultze D (2007) Fließeigenschaften von Schüttgütern und verfahrenstechnische Siloauslegung. Schwedes und Schultze Schüttguttechnik GmbH, Eigenverlag, Braunschweig, www.schwedes-und-schulze.de
56. Spliethoff H, Siegle V, Hein KRG (1996) Erforderliche Eigenschaften holz- und halmgutartiger Biomasse bei einer Zufeuerung in existierenden Kraftwerksanlagen; Tagung "Biomasse als Festbrennstoff – Anforderungen, Einflussmöglichkeiten, Normung", Schriftenreihe "Nachwachsende Rohstoffe" Band 6, Landwirtschaftsverlag, Münster, pp 155–175
57. Steenari B-M, Lindqvist O (1998) High-temperature reactions of straw ash and the anti-sintering additives kaolin and dolomite. Biomass Bioenergy 14(1):67–76
58. Temmerman M, Rabier F, Daugbjerg Jensen P, Hartmann H, Böhm T (2006) Comparative study on durability test methods for pellets and briquettes. Biomass Bioenergy 30:964–972